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SHM Structural Health Monitoring

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Increased awareness of the economic and social effects of aging, deterioration and extreme events on civil infrastructure has been accompanied by recognition of the need for advanced structural health monitoring and damage detection tools. Today, these tasks are done by visual inspection and very traditional methods such as the tap test. This labor-intensive task is done at a frequency of less than once every two years for bridges, and on an as-needed basis for other infrastructures such as buildings. Structural health monitoring techniques based on changes in dynamic characteristics have been studied for the last three decades. When the damage is substantial, these methods have some success in determining if damage has occurred. At incipient stages of damage, however, the existing methods are not as successful. A number of new research projects have been funded to improve the damage detection methods including the use of innovative signal processing, new sensors, and control theory. This survey paper highlights these new research directions.

Keywords structural health monitoring · damage detection · dynamic characteristics · infrastructure

1 Introduction

Civil infrastructure, which include bridges and buildings, begin to deteriorate once they are built and used. Maintaining safe and reliable civil infrastructures for daily use is important to the well being of all of us. Knowing the integrity of the structure in terms of its age and usage, and its level of safety to withstand infrequent but high forces such as overweight trucks, earthquakes, tornadoes, and hurricanes is important and necessary. The process of determining and tracking structural integrity and assessing the nature of damage in a structure is often referred to as health monitoring.

Ideally, health monitoring of civil infrastructure consists of determining, by measured parameters, the location and severity of damage in buildings or bridges as they happen. However, the state-of-the-art methods of health monitoring do not give sufficiently accurate information to determine the extent of the damage. Currently, these methods can only determine whether or not damage is present in the entire structure. Such methods are referred to as "global health monitoring" methods. They are important because

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often just knowing that damage has occurred is all that one needs so that further examination of the structure to find the exact location and severity of the damage can be taken.

Non-destructive evaluation methods are used to find the damage. Methods such as ultrasonic guided waves to measure the state of stress, or eddy current techniques to locate cracks can determine the exact location and extent of the damage. These methods are "local health monitoring" methods. Non-destructive evaluation (NDE) is often time consuming and expensive, and access is not always possible. Therefore, both global and local health monitoring are necessary. NDE techniques are discussed in a different article [7]. In this article, we concentrate on global health monitoring issues. A number of new research projects have been funded by the National Science Foundation to improve the damage detection methods including the use of innovative signal processing, new sensors, and control theory. This survey paper highlights these new research directions. It is intended to provide the readers thoughts on the future outlook of health monitoring technologies. An extensive literature review of structural health monitoring methods can be found in Doebling [10,11] and Hemez [15].

Global health monitoring has been the traditional tool used to determine the safety of bridges. The Federal Highway Administration mandates evaluation of condition of bridges every two years. These evaluations typically consist of visual inspection and tap tests – listening to audible variations in response to tapping the bridge surface to determine if voids or de-bonding exist. However, tap tests are limited to finding voids near the surface of concrete, de-bonding of wraps, and in some cases significant cracks. As a result of this simple evaluation, bridges are rated for their safety and reliability. The US has a bridge inventory of over 500,000 highway bridges with a span length over 25 ft. The large number of bridges combined with a small staff make this modest biannual period of bridge inspection not always achievable.

Bridge ratings are supplemented by the use of finite element analyses. The problem with these analytical methods is that the structural model is not known for most buildings and bridges. Models are usually based on best guesses of what may be in the as-built structure. Another problem is that the condition of aging structural members is not known.

Current federal spending in the US for replacement of structurally obsolete bridges based on these rating methods is approximately $10 billion per year [8]. Although based on current best practices, the inaccuracy of the current rating methods result in the retrofitting or replacement of many bridges that, in some cases, need not be retrofitted or replaced. Worse is the possibility that some bridges needing engineering renewal or replacement are not identified.

Another important use of health monitoring is to estimate the service condition and the remaining service life of the structure. Recorded data for strain on supporting members of a bridge can be used to obtain vehicle weight (weigh-in-motion), vehicle count, environmental conditions such as wind load and temperature variations. These data in turn can be used to help estimate the structure's safety and reliability. Currently in the US, more bridges are being replaced because they are functionally obsolete than because they are structurally unsound [8].

2 Overview of Global Health Monitoring Techniques

Most global health monitoring methods are centered on either finding shifts in resonant frequencies or changes in structural mode shapes. The premise that changes in the dynamic characteristics of a structure indicate damage is compromised by the fact that temperature changes, moisture and other environmental factors also produce changes in dynamic characteristics. If the causes of changes in dynamic characteristics other than damage are considered to be noise in the measurement, then the changes due to damage must be significantly larger than the noise in order for the techniques to work.

Early works in health monitoring found that loss of a single member in a structure can result in changes in the fundamental natural frequency of one to as much as thirty percent [2,33]. Indeed, if a member is not strained in the fundamental mode, then the loss of that member has no effect on the fundamental frequency or mode shape. By the same argument, if the structure was statically determinate, then the loss of any member would result in an unstable structure. In concrete structures where most of the stiffness is contributed by the concrete, the deterioration of the reinforcing steel has been shown to have little influence on the natural frequency [14]. In highly redundant structures such as shells, damage in the form of a notch produced changes in the dynamic characteristics that were not measurable [31]. It is easy to see that some forms of damage may not affect the frequency at low levels of vibration; e.g. the lost of a bolt in a connection with several bolts may appear to be fixed because the friction provided by the remaining bolts may be sufficient to keep the members to the connection from rotating at low levels of forces. Although the loss of important members in a structure does result in measurable changes in natural frequencies, this approach cannot capture many forms of damages. Therefore, it provides only necessary, but insufficient conditions to fully assess or characterize damage in a structure.

Another level of sophistication of health monitoring approaches proposes to find the length and location of cracks based on the natural frequency shift [30]. Most of these methods stipulate that the only form of damage is cracking, and by extension loss of cross sectional areas. These assumptions limit the method to some very special situations.

Damaged members cause changes in mode shapes as well as natural frequencies; mode shapes changes are, however, more subtle. Damage is a local phenomenon and may not significantly influence the lower frequency global response of structures typically measured during vibration tests. Early researchers [13,24] found that mode shapes changes are not sensitive to local structural damage. Many early methods assume that damage is the result of cracks only, and that damage is concentrated in a few members. For concrete bridges, cracks are pervasive. For steel bridges, major cracks as assumed by the early researchers are probably the only kind of damage that can be easily recognized by visual inspections. Location of damage due to corrosion, connection problems, material degradation, etc. cannot be found by these methods. Also, measuring mode shapes is not a trivial matter. In fact, if mode shapes can be measured, then why not measure the deformation, which is probably easier to measure, and it can be used to determine the damage as well.

When only a few members are damaged, an improved method to detect the location of damage is to use the curvature of the mode shape [25]. The curvature of the mode shape appears to be more sensitive to loss of stiffness due to member damage than the mode shapes themselves. For example, loss of a member may cause a sudden change in the mode shape's first derivative (slope) and second derivative (curvature or strain). Observation of these modal derivatives, particularly strain because it can be measured easily, may help locate the damage in the structure [5]. However, if the damage is distributed throughout the structure, strain may not be a good indicator of damage if a baseline measurement data set of the undamaged structure is not available. Even without the baseline data set, it is possible to locate damage by observing anomalies in the deflection profile or changes in curvature [32,36]. Another alternative to mode shape is the use of the load dependent Ritz vectors, also known as Lanczos vectors [4,20]. Sohn [29] found these vectors to be more sensitive to damage than mode shapes.

Another class of global health monitoring methods is the matrix update method, which is based on the modification of the mass, stiffness and damping matrices of the structure to match measured data as closely as possible. These methods attempt to minimize error with respect to measured responses through optimization techniques [10,14,23,37]. The problem is that the baseline stiffness, mass, and damping matrices are probably inaccurate to begin with. Even if they were accurate, the solution of the optimization is not unique. Furthermore, there is no guarantee that the resulting stiffness matrix is positive definite. The connectivity of the elements, which is manifest as bands in the stiffness matrix, is not enforced. The error minimization process often changes the stiffness terms of elements that are not damaged; there appears to be no practical way to limit changes of stiffness to the damaged elements only [18]. Therefore, a local minimum obtained in this manner is not guaranteed to identify the damage location.

A statistical pattern-recognition approach using Bayes theorem determines the most probable damage event by comparing the relative damage probabilities of different damage events. Statistical data are obtained from continuous or periodic ambient or forced vibration measurements. The relative damage probability of a damage event is obtained by using the difference between the measured frequencies and mode shapes and those predicted by the analytical model. Both measurement and modeling errors can be explicitly considered [29]. The goal of the approach is to determine if the measured parameters come from a healthy or damaged structure.

Artificial neural networks (ANN) have recently been used to recognize the strain measurements based on a set of training examples that represent different types of damage in a structure. The examples map a specific damage to a set of strain measurements. Although ANN can map new patterns of strain readings to new damage type and location, the results are only accurate if the pattern matches one of the examples of the training set. With a limited set of training examples, convergence is not guaranteed [21].

The methods described are all able to predict damage and find the location of the damage to some degree. They tend to do better when the damage is severe, and if the damage type matches those assumed. If only the loss of large and important members may result in significant shifts in natural frequencies, then perhaps a visual inspection would suffice in finding the damaged member(s). Nevertheless, these methods have some success if only a few members of a structure are damaged. As the number of damaged members increases, the number of measured modes from the damaged structure must also increase or the mapping from stiffness reduction to measured frequencies become ill conditioned in the subspace spanned by the measured modes. This requirement is difficult to meet because shaking the damaged structure to the point that higher modes are activated may not be a good idea if the damaged structure is to be salvaged.

Environmental effects such as temperature variation and moisture variation can introduce severe noise in the reading. Combined with the fact that typical damage to the structure is small; the signal-to-noise ratio is often not large enough to determine the extent and locations of the damage based on the global dynamic characteristics of the damaged structure. In addition, methods based on the use of stiffness, mass or damping matrices suffer from the fact that these matrices are computed based on idealized situations not likely to be found in real life. Predictions of damage by using these matrices can be severely compromised in some cases.

3 Recent Health Monitoring Methods in USA

A novel method to monitor cracks in structures is the use of imaging and pattern recognition methods [35]. Cracks reflect or absorb light differently from the neighboring region. Applying a threshold to retain a certain level of gray to an image of a structure, it is possible to retain the cracks in the image. However, it is difficult to determine the optimal threshold level because the gray-levels vary significantly among images and regions within an image. Methods to obtain the threshold are usually based on the average gray-level of an image. Most of the cracks are usually identified along with some areas without cracks. A connected component object identification process is then used to remove the noise (patches on the image that do not represent cracks). This method is limited to the identification of surface cracks on visible areas only.

Responses of a damaged structure provide a "snap shot" of the structure from which damage can sometimes be identified. If the damaged structure can be further modified, then the modified structure can provide another "snap shot." For example, if a member of the damaged structure is removed, then the response of the modified structure may change significantly if the damage is such that the removed member is highly stressed and important in maintaining structural stability. This kind of modification can be easily achieved if the structure is fitted with active or semi-active controllers. Damping of members or even stiffness can be changed by the use of these controllers. Suppose a structure is equipped with four controllers, and each controller can be set to two stages: on and off. Then a total of 16 different modifications can be achieved. These modified structures may help identify the location of the damage [28].

The Damage Locating Vector (DLV) approach is a theoretically based technique for mapping changes in flexibility to the spatial distribution of damage [3]. The principle behind the method is the fact that the null space of the change in flexibility provides vectors that, when treated as loads on the structure, lead to stress fields that are zero over the damaged portion of the domain. An appreciation of why this is so can be gained by noting that the null space of the change in flexibility contains vectors that lead to identical displacements (at the sensors) in the undamaged and damaged states. Indeed, with F_U and F_D as flexibility matrices in the undamaged and damaged states the equal displacement condition is

$$F_U L = F_D L \quad (1)$$

or

$$[F_D - F_U]L = [D_F] \quad L = 0 \quad (2)$$

which shows that L is in fact in the null space of D_F It is not difficult to see that a sufficient condition for a load vector to be in L is that the stress field that it induces in the system is identically zero over the damaged elements. The fact that the condition is also a necessary one has been shown by Bernal [3]. The DLV localization is in principle carried out by computing the null space of D_F, treating the computed vectors as static loads on the system and identifying the damage as the intersection of the regions of zero stress. In practice, of course, imprecision and truncation require that the null space and the "zero stress region" be defined using nonzero finite thresholds. Methodology for selecting these thresholds objectively, as well as other issues associated with the DLV technique are presented in Bernal [3].

It is well known that environmental factors such as changes in temperature and moisture can add substantial noise to damage signals. Methods based on comparison of signals from a damaged structure to baseline signals of the undamaged structure suffer from this problem. In offshore structures, environmental changes may include growth of marine vegetation on the structure that changes the mass of the structure, thereby changing the dynamic characteristics of the structure. A method to minimize the effects of environmental changes is to eliminate the use of baseline signals. Chen et al. [9] eliminates the need for baseline signals by observing the transient changes of vibration signals. As the structure vibrates, the surfaces of the crack come in contact and rub. After a few minutes of vibration, the surfaces of the crack have changed sufficiently to affect the measured signals. In this way, the comparison of signals are based on the same structure taken only a few minutes apart, and therefore, insensitive to the environmental effects that often change after much longer period of time.

Another method to increase the signal to noise ratio is the use of wavelet. Merits of wavelet analyses lie in its ability to examine local data with a zoom effect. This zoom effect can provide multi-levels of details and approximations of the original signal [16]. Damage and the moment when the damage occurs can be detected by a spike or an impulse in the time–frequency plot. The signal to noise ratio can be increased by using wavelet decomposition, and location of the damage can be identified by patterns in the spatial distribution of spikes. The wavelet approach can tolerate noise level of 20% of the signal. When noise level reaches over 100% of the signal, detection of the spike is difficult. In addition, damage has to occur during the monitoring period. Therefore, this method is suitable for continuous monitoring only. Modifications of this method by using wavelet packages have extended the method to detect existing damages. A similar approach is the use of Hilbert–Huang

Table 1 Comparison of signal feature extraction among HHT, wavelet, and fourier spectral analyses.

	Fourier	*Wavelet*	*HHT*
Decomposition	Frequency space	Scale/Frequency	Time Space
Basis	Fixed a priori	Fixed a priori	Adaptive
Frequency Determination	Convolution/global	Convolution/regional	Differentiation/local
Presentation	Energy-frequency	Energy-frequency-Time	Energy-frequency-Time
Feature Extraction	No	No for Discrete Yes for Continuous	Yes
Nonstationarity	No	Yes	Yes
Nonlinearity	No	No	Yes

Transform [17] where the measured signals can provide additional information even in cases when the structural behavior is nonlinear and non-stationary. Table 1 highlights some of the differences of these methods.

An alternative approach for structural health monitoring that does not use modal properties is to represent the dynamic response of a structure in terms of the superposition of traveling waves that can traverse individual elements of a structure, reflecting off boundaries to establish standing waves from constructive interferences. Damage is then identified by using these traveling wave components. Pines [26] uses this approach by creating a dereverberated transfer function (DTF) that measures the steady state response of a structure when incident waves do not reflect off internal or external boundaries. The DTF is used to infer the presence and location of damage by examining the relative phase lag error between successive degrees of freedom. Detectable phase lag can be observed in a three-degree-of-freedom structure when damage is introduced. However, it is not clear if damage is detectable for structures with hundreds or thousands of degrees of freedom. The ability of this method to be effective in the presence of high noise levels is also not clear.

A method that circumvents the problem of noise and the small changes typical of the dynamic characteristic methods is the use of actuators and sensors such as piezoelectric materials. A typical application consists of a patch of piezoelectric material that is used as both an actuator and a sensor [19]. The patch is placed over an area vulnerable to damage such as a bolthole. The material is excited and simultaneously senses the response of the structure. Damages such as cracks and material degradation cause the sensed signals to change. Analysis of the novelty in the response signals (novelty detection) allows the determination of damage location as well as the nature of the damage [34]. As long as baseline signals of the undamaged structure are available, detection of damage is very robust.

This technique is being applied to civil infrastructures to detect debonding of steel reinforcement bars in concrete [6]. Although environmental factors are present as always, the damage induced change in signals in the sensor–actuator method can be much higher than those caused by the environment. However, while paths for vibration signals in relatively homogeneous metal used in aerospace structures can be predicted with a high degree of accuracy, the same cannot be done for concrete structures with random sizes and shapes of aggregate. Microscopic cracks in concrete can significantly change the propagation of signals in the structure; yet they may not have any significant effect on the structural strength. These differences make the application of this approach to civil infrastructures a challenging one.

4 Sensors for Health Monitoring

As new sensors become available, the possibility for application of improved structural health monitoring techniques are increasingly feasible. These new sensors include Micro-electromechanical System (MEMS) devices for accelerometers and other applications, nuclear magnetic resonance (NMR) capsules to detect chloride ions, shearography to detect out-of-plane displacements caused by delamination, LIDAR to capture 3D position of objects, infrared thermography to detect debonding, and others. These new sensors typically target the monitoring of one specific type of damage; for example, concrete cracking, cable breakage, steel reinforcement corrosion, and delamination or debonding. Although everyone of these measurement is important, it is important to realize that any particular one of these methods do not, in general, give the picture of the overall health of the structure.

Acoustic approaches such as acoustic emissions, ultrasonic measurement, impact-echo and tap tests are well proven technologies that are used to evaluate local conditions of the infrastructure. Innovations in this area such as the use of air-coupled devices have made application of these approaches significantly easier. Some of these techniques such as the tap test are very robust and inexpensive; consequently, they are often used in spite of being labor intensive.

Another robust technique is the use of X-ray and Gamma ray to get visual images of the interior of structures such as steel cables and slabs. This method is easy to understand, and has a wide base of acceptance. Its major detraction is that the size of the equipment makes it difficult to reach locations with difficult access such as the bottom of the deck of a tall bridge or the steel tower of an off-shore structure. Another problem, also associated with access, is the need to have access to both sides of a structure when often even access to one side is difficult. Recent research using back-scattered signals has mitigated this problem.

Radar technology has recently seen many new innovations in the area of sensing. Major innovations include the development in ground penetrating radar and broadband radar. Application of these radar techniques in conjunction with improved signal processing have made it possible to obtain three dimensional views of reinforcing steel in concrete slabs while traveling at highway speeds [1].

Recent developments of fiber optic sensors have made distributed sensing possible. New fiber optic sensor capabilities include measurements of cracks in concrete and vehicle counting. The uses of chemical coatings have further increased their use to detect the presence of chloride ions, and by extension corrosion of reinforcing steel in concrete. Although fiber optics can theoretically multiplex for infinite number of sensors, the useable frequency range and the dynamic range of the sensors limit the number of sensors on each cable to as few as four sensors. Other disadvantages of fiber-optic sensors include the need for installation during construction, the need for skilled labor to install the sensors, and the relatively high cost associated with the data acquisition equipment. A similar method that avoids some of the disadvantages of fiber optics is the use of coaxial cable as sensors [22]. These cables are more robust, and they require less expensive and specialized equipment to obtain the signals.

Sensors are being deployed in civil infrastructures. However, the recorded data for long-term monitoring are extensive. Much of such data are being collected but not used because processing of the data is too costly. One way to get around this problem is to develop new sensors that are capable of processing the data before the output is recorded. Such smart sensors would reduce the amount of data that need to be collected and would distribute the computing effort. Another class of smart sensors consists of those sensors that can communicate with each other. The concept of nano-dust is a network of small sensors that are capable of communicating among themselves. When they are combined with other sensors, the result can be a powerful network of sensors that can both use neighboring sensors' data, and communicate the sensed data wirelessly by hoping from one sensor to another.

Wired sensors have limited application because they usually need to be installed during construction. The wiring can also be a problem as wires get in the way of the function of the structure and limit the number of sensors that can be deployed. Wireless sensors are meant to eliminate these problems. Wireless sensors used so far are mostly powered by batteries. The batteries may be supplied by solar power, which omits the need of being close to an AC source. Unfortunately, these applications require wires nevertheless. The claim to being wireless refers usually to the fact that the transmission of data from the sensor to the data acquisition device is done wirelessly. In the near future, wireless sensors should be tetherless.

Fault detection methods have been used for health monitoring of aerospace and mechanical systems. These methods are based on the comparison of model output and sensed signals. When the sensed signals are significantly different from the predicted output from the model, it is likely that damage has occurred. Pattern recognition is then used to identify the damage location and level of damage. These methods rely on an accurate model to predict the output parameters. In civil infrastructures, these methods are generally classified as stiffness or flexibility identification methods, in which the measured data are compared to the model prediction. Differences between measured data and model prediction are used to adjust the model. The adjusted model is then compared to the original model to determine the possible location and level of damage. These methods depend on the accuracy of the analytical model. In civil infrastructures, the analytical model of the undamaged structure may not be sufficiently accurate to yield consistent results.

5 Conclusions and Outlook

Global monitoring methods based on dynamic characteristics work adequately when the damage to the structure is substantial such as the loss of a primary element of the structure. Damage to the structure such as concrete cracking, yielding of steel, or typical deterioration of material result in small changes in the dynamic characteristics. When the noise level is limited to 20–25% of the signals from the damage, nearly all methods are able to detect the damage. In real life, environmental factors such as change in temperature, moisture, and wind may result in signals larger than those caused by the damage. In these situations, global monitoring methods based on dynamic characteristics are not sufficiently sensitive to detect damage in the structure [12]. Various methods to increase the signal to noise ratio have improved the damage detection algorithms.

Dependence on baseline data is a significant problem in global health monitoring as environmental effects such as temperature can change the signals from an undamaged structure significantly. When damage to a structure produces changes smaller than these environmental effects, detection based on baseline data must be augmented by methods that minimize the environmental effects if the damage is to be detected with any level of accuracy. Methods that are based on novelty detection have the advantage that no baseline data are needed. In these methods, quantifying the damage may not always be possible.

Unlike aerospace or automotive structures, civil infrastructures are not built with the same level of precision. In many cases, because of on-site construction constraints and change orders, the structure is not built according to the archived design. Accuracy of implementation is often an issue, and uniformity of material is never guaranteed when concrete is used. On top of these inaccuracies, models based on idealized behavior such as perfect pin or fixed connections can never be achieved. Availability of data to obtain an accurate analytical model is often not possible. This problem makes model-based health monitoring of civil infrastructure a challenge.

The complexity of civil infrastructure problems has limited the monitoring methods to reliance on linear analytical models. Cracking and other damage to the infrastructure as well as the behavior of the material often makes their behavior nonlinear. Using linear assumptions in these situations may provide only an approximate prediction to the health of the structure.

Signal-to-noise ratios need to be boosted because small damage produces changes that are often below the noise from environmental effects. Many new techniques attempt to increase the signal to noise ratio. Some of these are done by filtering the unwanted signals such as the removal of the environmental effects. Other methods attempt to boost the signal to noise ratio by using analytical tools such as wavelets or Hilbert–Huang Transforms. These methods are usually an improvement over the earlier methods as long as the noise is not unreasonably large. When the noise is many times larger than the signals from the damage, no amount of signal boosting can make the method accurate.

Local monitoring techniques are much more likely to locate and quantify the damage. However, local monitoring of all infrastructures in a timely manner is not a realistic goal at present. The Federal Highway Administration has a 2-year cycle for visual inspections of the current bridge inventory. Even this low level of inspection schedule is not always possible. Buildings that are not owned or managed by a single entity are even less likely to receive this level of monitoring.

Global monitoring to detect existence of damage, and sometimes both existence and location of damage, should be combined with the use of local monitoring techniques to obtain a better picture of the local damage. Monitoring should go beyond the detection of damage. Monitoring of the loading, for example, can be just as important because it can forecast damage. If the load cycles and/or amplitude of the load are significantly higher than the design load, then it is not difficult to predict that damage could be premature.

Further work on damage detection should include: (1) advanced sensing systems with improved and optimized placement of networkable sensors, (2) tetherless sensors and data transmission system, (3) advanced signal processing techniques to increase signal-to-noise ratios, (4) damage model development for infrastructures, building, and components, and (5) software and hardware integration.

Cost of sensors has been a limitation on the number of sensors that have been deployed. Only thirty years ago, use of one to three accelerometers on a structure was common practice and considered acceptable. Today the price of sensors make it possible to place close to a hundred sensors on a single structure. On heavily instrumented structures such as long-span bridges, as many as 600 sensors have been used. Ultimately, the number of sensors on a structure should be sufficient to make global monitoring approach local monitoring on a large scale; thereby eliminating many of the problems associated with global monitoring that we encounter today.

As global monitoring approaches local level monitoring, the density of sensors requires that they be wireless in the sense of being completely untethered. They need to be inexpensive and easy to apply, so that they can be attached to existing structures with little effort.

In civil infrastructures, continuous monitoring requires the use of robust sensors that can withstand the damaging effects of the environment and the alkali or salt that are often associated with infrastructures, since these sensors are expected to operate for the life of the infrastructure that may be as long as 50 or 100 years. Robust sensors are expected to perform reliably for the life of the structure. That is the reason the tap test is still performed in spite of the fact that it is time consuming and imprecise. The robustness of the tap test, where it can be applied, is unmatched.

Non-destructive evaluation techniques remain as one of the important part of health monitoring of civil infrastructure. Their ability to specifically identify one type of damage may be viewed as a useful part of damage detection, as global methods often do not give enough information to determine the exact mode of failure.

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