Chapter 1

Introduction

1.1. Background (Structure damage and failures)

Innovation is a continuous process in area the structural analysis. For fulfilling this requirement focus should be made for the development of robust and reliable smart structural parameters and damage detection systems (SPDDS) for different civil engineering structures. At initial phase before the occurrence of damage, various mechanical parameters get affected. To address the initial change in mechanical parameters before and after the damage is an area where research and development is still under progress. C.K Soch et al. discussed that damage in structure may occur due to fatigue cracks, corrosion, impact-induced delamination in composite structures, malfunctioning of expansion joints, and degradation of structural connections [28]. There exist various parameters on which level of damage depends; it includes the type and nature of the damage, damage location area, and life extension of damage, as shown in fig.1.1. Based on the above discussion, it became very important for developing a structural health monitoring system.

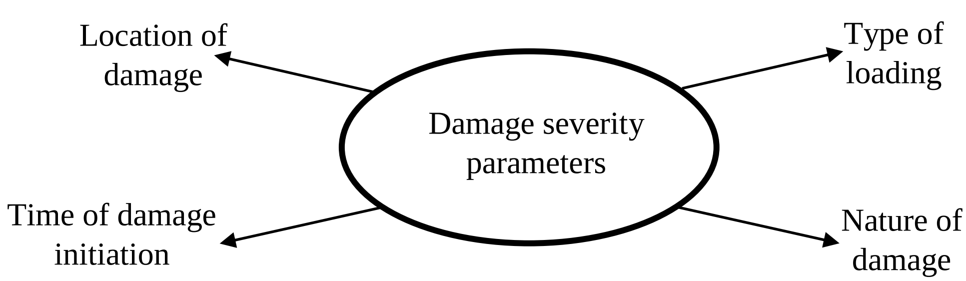

Fig. 1.1. Basic parameters on which damage depends

Deterioration of structure health is a natural phenomenon after the construction of any civil, mechanical, and aerospace structure due to external loading and extreme environmental conditions. Maintaining uniformity in the strength of any structure is the primary requirement for any reliable construction. Structures get affected by variation in loading and time duration of the same. Load, environmental conditions are other factors that contribute to the reduction in the strength of the structure. Damage and failures also vary as per the type and area of structures. For example, the threshold level of aerospace structures is much lower as compared to civil and mechanical structures. Damage in structures can be explained as a condition under which structure loses its strength due to which structure fails to perform the required function. M. Gorden et al. briefly discussed inability in the performance of a component or member of a structure beyond a threshold level is termed as failure [53]. Based on the mechanical analysis, the ultimate failure strength of a material system defines its maximum load-carrying capacity. In a safe design, the system's load-bearing capacity is kept lower than the ultimate failure strength of the material. To counter failure, it becomes essential to detect damages timely and thus contribute to maintain the health of the structure.

1.2. Requirement of SHM

Timely monitoring and maintenance help in increasing the service life of a structure and improve its reliability. It also helps in the prevention of catastrophic failures of structure and components. Continuous loading and variation in the type of load make it more relevant to check and maintain the health of the structures. Damage is the initiating stage of failure of a component or structure. Civil and mechanical structures contribute an important part in the infrastructure and transportation of the nation. J.M. Ko et al. briefly discussed that significant part of every country's economy is being spent on maintenance and monitoring of many expensive civil and mechanical structures. As discussed earlier, the evaluation and performance of the structures became mandatory to avoid failure. If a structural strength falls below the threshold level, then failure occurs, which ultimately causes accidents and loss of life in many cases. Method of early damage detection and maintaining the serviceability of structure is the primary requirement in the present engineering design concept. Nature is another factor that can affect the working capability of the structure. Structures must be periodically monitored for maintaining its integrity. Periodic monitoring of the health of the structure also provides valuable information related to material behavior under different conditions. Structural health monitoring provides a systematic procedure that ultimately helps in reducing the catastrophic failures and is helpful in online damage assessments of structures. Monitoring the structures also helps in quantifying the level of damage and also helps in the early detection of damage in structures. The structure design is generally done for a specific time period within which the structure is supposed to function satisfactorily. Proper and periodic health monitoring of a structure provides better and long-time serviceability, which ultimately contributes to the economic development of a nation.

In general, a typical SHM framework incorporates three significant parts: a sensor framework, an information preparing framework (counting information procurement, transmission, and capacity), and a well-being assessment framework (counting indicative calculations and data the board). The sensors used in SHM are required to screen not just the basic status, for instance, stress, strain, displacement, acceleration, etc. and so on yet in addition influential environmental parameters, like wind speed, temperature, and therefore, the quality of its foundation. Various dimensions of SHM is shown in fig. 1.2.

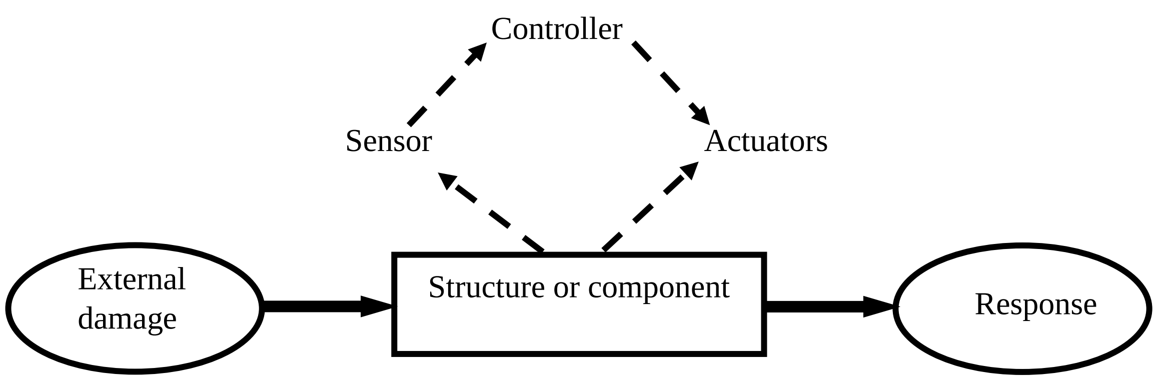

Fig. 1.2. Structure health monitoring system

Non-destructive testing (NDT) means the testing of the specimen or material without interfering with the working of the main structure. Various types of non-destructive testing techniques exist in present SHM methodology. Visual inspection is one of the oldest methods which is successfully used on a regular basis. But with the advancement in the construction of complex structures, only visual inspection can't be considered as a reliable methodology for monitoring the health of a structure. The conventional visual inspection method carries the disadvantages of being both expensive and time-consuming. Different emerging SHM based technology includes ultrasonic based methods, impact echo technique, rebound hammer, and many more. Some of the advance SHM techniques are shown in fig. 1.3.

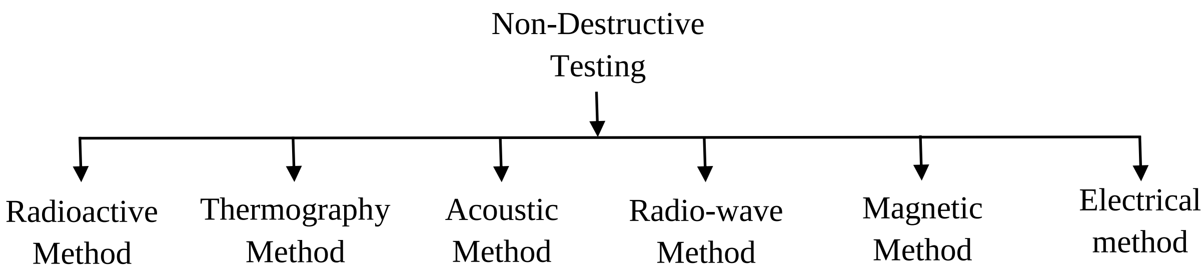

Fig. 1.3. Main categories of NDT methods for SHM

The fast technical development in the area of sensors, data acquisition and communication, signal analysis, and data processing has boosted SHM with significant advantages. SHM generally provides useful data for real-time monitoring of structures. Health monitoring of structures can be periodic or continuous, short term or long term, local or global. Sensors are added to the system, which may vary from few to large number depending on the structure size. Recent research has contributed to the application of NDT methods in SHM, but yet there exists a lack of expert opinion and understanding for a successful implementation. The major elements of the SHM are shown in fig. 1.4. The type of structure is a crucial element for any SHM method. SHM for large structures always comes with difficulty to handle compared to short structures. Sensors are another part of SHM method, which plays a vital role in the health monitoring of structures. Sensors are used for detecting the variation in structures that are related to damage phenomenon. In a small SHM system, a small number of sensors are required, whereas, in the global system, a large number of sensors are used. In local SHM, infrequent measurement is performed, but in global SHM, continuous measurement is performed. Data mining and transfer is another important element in SHM as data may be subjected to loss of some useful information. Proper management of data leads to cost-effective and economic health monitoring of structures. Interpretation of the output from the analysis provides valuable structural information which is used for maintenance and repair.

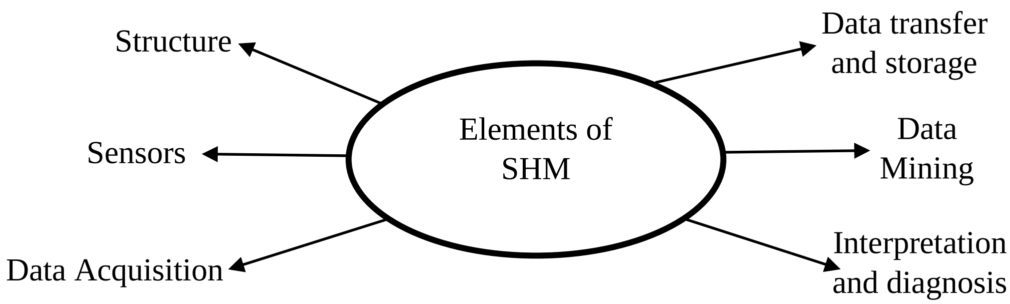

Fig. 1.4. Elements of structural health monitoring

A key component of an SHM framework rather than non-destructive testing (NDT) approach is the high procedure of mechanization. The observing framework ought to choose independently whether the host structure is unblemished or damage. An essential prerequisite for the acknowledgment of such a framework is, that the sensors are permanently installed on the structure. In this way, standard estimations become accessible that can be utilized in the resulting signal analysis and decision making. A wide scope of implanted and appended sensors have been invented for SHM applications, including strain checks, accelerometers, fiber optic sensors, dynamic ultrasonic sensors, inactive acoustic sensors, remote sensors, and so on. Among them, the fiber optic sensor has been rising as an undeniably significant tool for SHM because of their remarkable points of interest in affectability and multiplexing ability. Steps of NDT based structural health monitoring are shown in fig. 1.5.

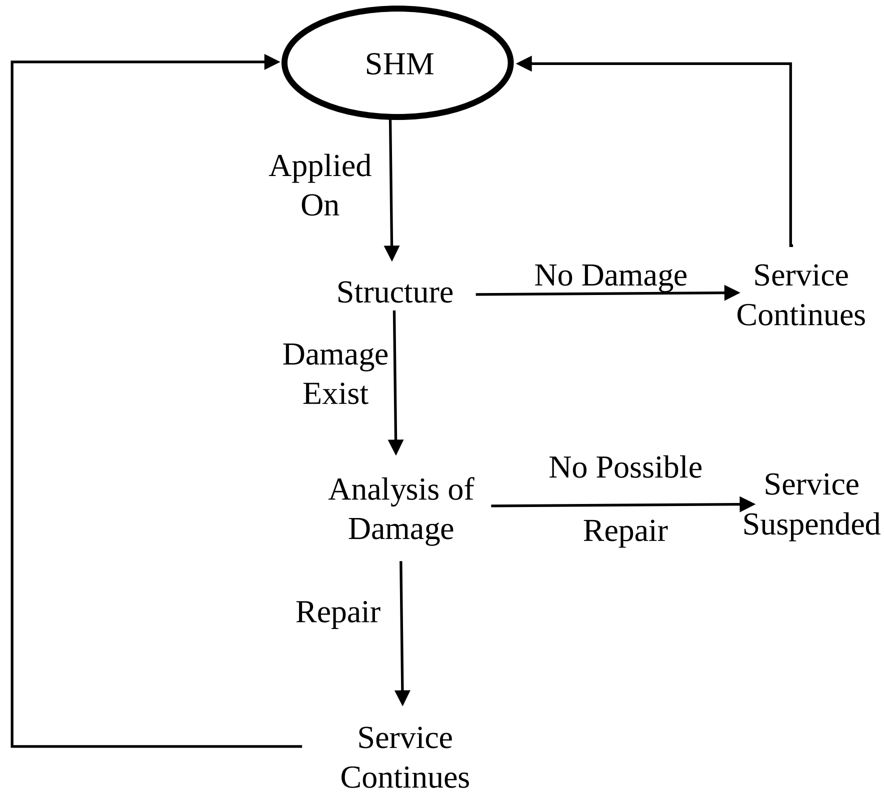

Fig. 1.5. Flow chart of structural health monitoring

1.3. Existing SHM Techniques and limitations

Structural Health Monitoring (SHM), as the name suggests, attempts to access the 'health,' i.e. the ability of the structure to fulfil its intended use for the general life span of the structure. It provides real-time data about the status of the structure. One of the main advantages of this technology would be in the aviation sector. There is a large amount of inspection that is done at regular intervals. To date, primitive methods like visual inspection using a magnifying glass are used. Surface cracks detection non-destructive methods like dye-penetrant, and magnetic particles are the most commonly used methods for investigation. This requires skilled personnel and is time-consuming.

Not only is it a waste of capital but also the time resources of skilled people. Untimely failure of structures leads to loss of life and property. Hence one needs a mechanism to identify the damage before it causes failure and is at its infancy. An advanced system is required, which provides real-time data about the location, and the extent of the damage that occurred. Structural Health Monitoring attempts to do just that. The main application areas are in dams, buildings, bridges, nuclear power plants, pressure vessels, aerospace systems like aeroplanes and rockets. It is ideal to be used in the cases where the loads are unpredictable, and the cost of inspection and maintenance is high, the aerospace industry is one such sector. In short, Structural Health Monitoring can help in warning a potential failure causing timely evacuation that can save lives and minimal damage to property.

Structural health monitoring is a method used for diagnosing the present state of a structure. A definitive objective is to identify the presence, area, and level of damage in a structure. This technique has pulled in much consideration in both areas of innovation and research. The method toward executing a damage detection and its characterization technique for structures is alluded to as Structural Health Monitoring (SHM). Here the damage is characterized as changes to the material and geometric properties of an auxiliary structural framework, including changes to the limit conditions and framework availability, which antagonistically influence the framework's performance.

For long haul SHM, the yield of this procedure is occasionally refreshed data in regards to the capacity of the structure to play out its proposed work considering the inescapable maturing and degradation coming about because of operational situations.

After outrageous occasions, for example, seismic tremors or impact stacking, SHM is utilized for quick condition screening and plans to give, in close to constant, solid data in regards to the respectability of the structure. The SHM procedure includes the perception of a structure after some time utilizing occasionally tested powerful reaction estimations from a variety of sensors, the extraction of damage sensitive features from these estimations, and the measurable examination of these highlights to decide the present condition of the structure.

Visual inspection is still the easiest and most common methodology used for identifying the external damage of structures. As the damaged area is identified, then techniques like radiography, eddy currents, thermal imaging, magnetic field analysis, electromagnetic impedance, acoustic, and ultrasonic can be used for assessment and quantifying the level of damage. A major limitation of this system of inspection is that it is not possible to access the damaged area after installation. This approach is sometimes very complex and expensive. Moreover, the visual inspection is completely dependent on the experience and expertise level of the evaluator.

In the last few years, development is made in the area of structural health monitoring by replacing the physical visual inspection with the automated monitoring systems. These automated systems have their advantages like fast assessment and reliability. The development of smart material is another emerging area where advance material systems are used in conventional structures. But these smart material systems are expensive and not easily available. So an online monitoring system became the requirement of present civil and mechanical structures.

Some of the SHM techniques that have been developed to quantify and locate the damage in the structures are based on the global or local interrogation of the structure. One of the disadvantages of using global dynamic techniques is that when the model is subjected to low-frequency excitation, only the first few mode shapes are obtained, and their corresponding natural frequencies can be obtained. But since localized parameters cannot alter global parameters such as natural frequency, curvature mode shapes, and mode shape data; therefore, damages at an early stage cannot be detected. Moreover, there are more chances of the signals getting contaminated with noise due to ambient vibration of the low-frequency range. Other local damage detection techniques such as ultrasonic techniques, acoustic emission, and impact echo testing require expensive and sophisticated equipment as well as well-trained professionals.

In recent times, the electro-mechanical impedance technique is being successfully used in structural health monitoring. This technique has higher sensitivity than the conventional global methods. The sensitivity is closer to that of the local ultrasonic techniques and is straightforward to implement on large structures when compared to local methods. It does not require expensive hardware like ultrasonic techniques, and no probe is moved from one location to another. Piezoelectric patches have very low weight and have very less power consumption. Moreover, they are non-intrusive on the structure. Since they are very small, they can be placed in inaccessible locations. Hence this could save a lot of time and effort that goes into dismantling structures and components for the purpose of inspection. Also, since the installation of the piezoelectric impedance transducers is easy, so it is suitable for both the existing and to-be-built structures. Another under-appreciated advantage of the electro-mechanical impedance method is that both the transducers used for actuating and sensing are the same, and this helps to reduce the size of the system and the complexity involved in the wiring. Another significant advantage of using the electro-mechanical impedance method is that the piezoelectric patches can be added to the structure at any time in the life span of the structure. In spite of the many advantages, the method has some limitations also. The piezoelectric patch is sensitive to damages over a small zone only, usually within a meter range. Even though this is advantageous for monitoring components that are small, but it becomes a nightmare when employed for sensing over large structures like bridges and entire high-rise buildings. The above would require significant capital and would have a cumbersome wiring system and data collection and processing systems. However, we can choose the critical regions judiciously based on the simulations, etc. Another major limitation of the electro-mechanical technique is that since most of the structures are statically indeterminate, the failure of few joints would not harm the structure as a whole and would not impact the overall stability of the structure being monitored. This inability to assess the overall stability of the structure is a major drawback when compared with its other global structural health monitoring techniques

Another famous strategy for SHM, which is being used these days, incorporates fiber optic detecting procedure. A fiber optic sensor is a sensor that utilizes optical fiber either as the detecting component ("characteristic sensors") or as a method for relaying signals from a remote sensor to the electronic analyzer that processes the signals ("extraneous sensors"). Fibers have numerous utilizations in remote detecting as it accompanies numerous favorable circumstances, which incorporates its little size, no electrical force necessity, multiplexing abilities, and so forth. Optical sensors itself are effective to screen physical, biological, and chemical changes in the structure. Optical sensors give numerous points of interest over sensors. A comparison of conventional and fiber optic sensor is shown in table 1.1.

Table 1.1: Comparison between Fiber optic sensors and Conventional sensors

Characteristics	**Fiber-Braggs Grating**	**Conventional Electric Strain Gauges**
Electromagnetic field	Non Sensitive	Sensitive
Electrical conductivity	Non Conductive	Conductive
Weight	Light	Heavy
Corrosion	No (High resistant to Corrosion)	Yes (Coating is compulsory)
Measurement Distances	Can be in Kilometers	Limited
Multiplexing Capability	Yes	No
Fatigue resistant	Good	Weak
Temperature Sensitivity	Very High	Low
Cost of Installation	Low	High
Miniature Size	Very Less	High(Compared to FBG)
Remote Sensing	Yes (in Km)	Yes (but amplification is required at regular intervals)
Harsh Environment Working	Good	Bad

Contingent upon the area of the sensor, a fiber sensor can be named intrinsic or extrinsic. In light of the working and demodulation procedure, a fiber optic sensor can be additionally isolated into intensity, phase, and frequency or polarization sensor.

A wide scope of implanted and external sensors have been read for SHM applications, including strain sensors, accelerometers, fiber optic sensors, dynamic ultrasonic sensors, uninvolved acoustic sensors, remote sensors, and so on.

1.4. Aim and Scope (research objectives)

The main aim of this work is to develop a smart monitoring-based system for analyzing the physical condition of beam-like structures by deduction of mechanical parameters and damage location using signal analysis. From the data gathered by fiber optic sensors installed on a cantilever beam, mechanical parameters like surface strain may be approximated using neural network methodology. The neural network technique is also used for locating the damage present in the beam structure. A novel structural health monitoring approach combining machine learning and signal analysis techniques can be implemented. The aim of this work is to analyze structural integrity based on frequency domain parameters using neural network techniques. The second part of the study includes a comparative study of two methods developed in the present work. One of the methods is based on fiber optic sensor integrated neural network method (FOSINN), and the other is based on the diffuse wave analysis using wavelets (DWAW) for damage analysis problems. Therefore, the present study intends to bring a significant contribution to the fields of structural health monitoring for damage detection by developing two novel methods, namely FOSINN and DWAW.

The main objectives of the thesis are:

a) Provide a state-of-the-art technique for smart structural health monitoring integrated with the advancement of using neural network intelligence;

b) Provide a FOS-NN integrated system for strain prediction and damage location;

c) Provide a systematic approach for diffuse zone selection for structural health monitoring;

d) Investigate the time domain based diffuse wave analysis using wavelet mechanics;

e) Propose a method for damage detection using wavelet-based diffuse wave analysis

1.5. Thesis Organization

This thesis contains a total of seven chapters, including the present chapter. In chapter one, the essential background, along with the requirement of SHM is discussed. It also includes existing SHM techniques and their limitations. At the end of the chapter, the basic idea of research and thesis organization is provided. Chapter two provides a detailed review of structural health monitoring using sensors and different methodologies along with their applications. A brief description of the fiber optic sensor and diffuse wave sensor is also discussed. Moreover, the state of the art and formulation of the problem is presented in this chapter. In chapter three, different damage detection techniques based on conventional methods are discussed. This chapter also provides a basic idea of the integration of neural network in FOS and wavelet-based sensing for strain analysis and damage detection. Chapter four covers the details of the experimental part in the research, including setup and sample preparation and data acquisition system. A description of strain approximation and damage detection using a neural network-based fiber optic sensor is presented in chapter five. This chapter is divided into three sub-parts which carry different analysis for strain approximation under static and dynamic load along with damage location analysis. Chapter six contributes to the damage location technique using wavelet-based diffuse wave analysis. Finally, in chapter seven, the conclusion and recommendations for future prospects are presented.