Integrated approaches for non-destructive testing of construction materials and structures

Paritosh Giri

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WESTERN SYDNEY UNIVERSITY

Centre for Infrastructure Engineering
School of Computing, Engineering and Mathematics
Western Sydney University, Australia

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Abstract

Civil infrastructures include structures which are inherently large in dimension, geometrically complex with different elements and joints, and composed of different materials. Due to the diverse material properties, geometrical shapes and varied damages in these structures, the selection of a non-destructive testing technique is a challenging task. This thesis aims to highlight the need for utilising multiple standalone techniques or integrated approaches for non-destructive testing of diverse construction materials and structures. This way, the benefits of different sensor techniques can be utilised to develop a system which can overcome the limitations of conventional non-destructive testing techniques. For this, systems based on three major techniques, namely, laser displacement technique, microwave sensing technique and piezoelectric sensing technique is developed.

The displacement measuring property of laser displacement sensors is utilised to generate one-dimensional, two-dimensional and three-dimensional surface profiles and images of different specimens. These specimens are composed of diverse materials with different dielectric, chemical and physical properties. The developed system described herein can detect different surface flaws such as cracks, cuts and blowholes accurately. The developed system is fully non-contact and consists of a single robust and compact sensor which is undoubtedly an economical solution to surface flaw detection in a variety of materials used in construction.

The microwave imaging technique is developed for the non-destructive testing of planar and tilted construction materials in civil infrastructures. The developed system utilises a microwave antenna attached to the scanner and connected to the performance network analyser. The magnitude and phase of reflection coefficient are used to plot microwave images to detect hidden and surface flaws in a variety of materials including metals, dielectric materials, composite materials and cement based specimens.

In microwave imaging technique, the distance between the microwave antenna and the material, which is referred to as standoff distance is an important parameter for
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detection of flaws. The standoff distance should be kept constant during the scanning process, or there should be a proper compensation method to overcome any change in the distance. The undesired change in the standoff distance masks the indication of flaws. However, civil infrastructures are composed of construction materials with different geometrical shapes and sharp edges, and maintaining the constant standoff distance during the scanning process is a challenging task. For this purpose, a novel dual laser integrated microwave imaging system is developed. The developed system consists of a novel integrated sensing unit with two laser displacement sensors and a single microwave antenna that automatically follows the contour of the material under test at a constant standoff distance and generates microwave images. The proposed system performs contour following at the hardware level and does not require any calibration or complex compensation algorithm.

A piezoelectric based sensor technique is developed for the detection of gap and debonding in concrete based composite structure. The developed technique uses propagation properties of the guided waves in the metal and CFRP plate excited and received by piezoelectric based transducers attached to the external surface. The measurement is conducted with both fresh and hardened early-age concrete specimens. A piezoelectric actuator is excited using sine burst signal, and the generated wave is received by a sensor after propagation along the specimen. The received signal at different gaps and debonds is used to detect the flaws. In order to quantify the flaw, damage indices including the correlation coefficient, the peak-to-peak amplitude of the resultant signal and root mean square deviation are used. The proposed technique is relatively simple with small transducers, one-sided, non-destructive, and cost-effective solution for interfacial defect detection.

The development of these standalone and integrated systems highlights the need of different non-destructive testing techniques for applications in demand. The integrated approaches not only enable monitoring of diverse materials and structures but also assure accurate and reliable information from these structures. Therefore, the integrated non-destructive testing approach is a key to overcome the limitations of current methods in monitoring the integrity of in-service structures on a continuous real-time basis.
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Statement of Authentication

I, Paritosh Giri, declare that all the materials presented in the PhD thesis entitled ‘Integrated approaches for non-destructive testing of construction materials and structures’ are of my own work, and that any work adopted from other sources is duly cited and referenced as such.

This thesis contains no material that has been submitted previously, in whole or in part, for any award or degree in other university or institution.

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## Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>1-D</td>
<td>One-dimensional</td>
</tr>
<tr>
<td>2-D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3-D</td>
<td>Three-dimensional</td>
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<tr>
<td>AE</td>
<td>Acoustic emission</td>
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<tr>
<td>AOM</td>
<td>Acousto-optic modulator</td>
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<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
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<tr>
<td>CD</td>
<td>Calibration distance</td>
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<tr>
<td>CFRP</td>
<td>Carbon fibre reinforce polymer</td>
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<tr>
<td>CFST</td>
<td>Concrete filled steel tube</td>
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<tr>
<td>DA</td>
<td>Dielectric waveguide aperture</td>
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<tr>
<td>EMR</td>
<td>End of the measurement range</td>
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<tr>
<td>FBG</td>
<td>Fibre bragg grating</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
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<tr>
<td>IF</td>
<td>Intermediate frequency</td>
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<tr>
<td>I/O</td>
<td>Input/Output</td>
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<tr>
<td>ISU</td>
<td>Integrated sensing unit</td>
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<tr>
<td>LDS</td>
<td>Laser displacement sensor</td>
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<tr>
<td>LDV</td>
<td>Laser doppler vibrometer</td>
</tr>
<tr>
<td>LMS</td>
<td>Laser mirror scanner</td>
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<tr>
<td>NDE</td>
<td>Non-destructive evaluation</td>
</tr>
<tr>
<td>NDI</td>
<td>Non-destructive inspection</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
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<tr>
<td>OEWA</td>
<td>Open-ended waveguide antenna</td>
</tr>
<tr>
<td>P2P</td>
<td>Peak to peak</td>
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<tr>
<td>PNA</td>
<td>Performance network analyser</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
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<tr>
<td>PZT</td>
<td>Piezoelectric transducer</td>
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<tr>
<td>RF</td>
<td>Radiofrequency</td>
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<tr>
<td>RMSD</td>
<td>Root mean square deviation</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>ROM</td>
<td>Read-only memory</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistance temperature detector</td>
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<tr>
<td>SA</td>
<td>Smart aggregate</td>
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<tr>
<td>SAR</td>
<td>Synthetic aperture radar</td>
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<tr>
<td>SHM</td>
<td>Structural health monitoring</td>
</tr>
<tr>
<td>SMR</td>
<td>Start of the measurement range</td>
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<tr>
<td>S-parameter</td>
<td>Scattering parameter</td>
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<tr>
<td>TDR</td>
<td>Time-domain reflectometry</td>
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<tr>
<td>TLS</td>
<td>Terrestrial laser scanning</td>
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<tr>
<td>UMI</td>
<td>Universal motion interface</td>
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<tr>
<td>VHDCI</td>
<td>Very high-density cable interconnector</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage standing wave ratio</td>
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<tr>
<td>WSN</td>
<td>Wireless sensor network</td>
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Chapter 1 Introduction

1.1 Overview

Civil infrastructures are integral to people’s lives and are used in everyday life in the form of buildings, bridges, roads, tunnels, dams or power plants. These interdependent networks of infrastructures are an important asset as they ensure the smooth functioning of society, enabling economic vitality, the efficient flow and conservation of natural resources, and the comfort and safety of residents. These structures are inherently large in dimension, geometrically complex with different elements and joints, and composed of different materials [1]. These materials may be conventional such as concrete, steel and wood or composite materials including fibre-reinforced composites [2]. The failure of these structures can have catastrophic public safety and economic consequences. Early detection of damage and appropriate retrofitting will aid in preventing this failure, save expenditure on maintenance and replacement. This ensures that the structures operate safely and efficiently over its intended lifespan [3]. Hence, reliable techniques that are capable of assessing the structural health of these civil infrastructures are needed.

Structural health monitoring (SHM) has attracted much attention in recent years in both research and development in response to the need for safety, security, lower life-cycle costs, and post-disaster condition surveys. The state of integrity of structures is influenced by numerous factors and events like ageing, loads, earthquakes, fires, explosions, and collisions. The SHM program involves the selection and placement of sensors suitable for the measurement of critical parameters that influence the performance and health of the structural system and not just focused on damage detection [4]. Since the influence of individual events is the cause of disturbances, such as strains, cracks and vibrations, selection of appropriate sensors requires knowledge of the relationship between the events and their effects. The sensors utilised in SHM are required to monitor not only these disturbances but also influential environmental parameters such as wind speed, temperature and humidity. However, the key factor is the availability of appropriate sensor systems for measurement of the events under consideration regarding their efficacy, cost, and robustness. Taking these aspects into
consideration, many of the novel sensor systems have been developed over the past decade with the potential for effective health monitoring of civil structures. In certain instances, the advanced sensor systems have been effectively employed for health monitoring of structural systems. However, in the majority of cases, there are limitations mainly due to issues involved in the practical adaptation of the new technologies in civil structures.

In general, a typical SHM system includes three major components: a sensing unit, a data processing unit including data acquisition, transmission and storage divisions, and a health evaluation technique including diagnostic algorithms as shown in Fig. 1.1. Since a large number of sensors are involved in a health monitoring system, the acquisition, transmission and storage of a large quantity of data for such continuous monitoring is a challenging task [5]. It is imperative to implement sensors and collect data successfully for a health monitoring application. After the collection of data, it is equally important to transmit this data to the monitoring station. Next important step is to correctly interpret the data from various types of sensors to reach critical decisions regarding the health status of the structure.

**Figure 1.1:** Architecture of an SHM system.

SHM, in general, can be divided into global and local SHM. Global SHM refers to the monitoring technique which takes into account the overall characteristics of a whole structure such as a bridge, building and tower. Local SHM focuses on critical parts of a structure and is used for localisation and evaluation of defects. In many cases, local SHM is the only viable method for this purpose. One of the effective methods of local SHM which can be applied to the structure without damaging it is known in non-destructive testing (NDT) or non-destructive evaluation (NDE). NDT is a technique
which applies physical principles to determine the characteristics of materials or components of a structure and to detect/assess the inhomogeneities and defects without impairing the usefulness of such materials or components [6]. There are several NDT techniques prevalent today such as acoustic emission techniques, ultrasonic techniques, optical sensing techniques, thermal sensing techniques, electromagnetic sensing techniques and so on. These techniques have different advantages and different application areas. For instance, ultrasonic techniques have an advantage in detecting defects in conducting materials such as metals while may suffer from signal attenuation in a dielectric material such as concrete [7]. The electromagnetic sensing techniques have an advantage in testing dielectric materials over other techniques. However, health monitoring of individual member of a structure is not possible with a single technique because of the variety of materials used in the structure. Further, these structures in real-life are mostly composed of layers of materials which changes the material property significantly making it even harder for a sensing technique to assess them. For this purpose, it is of utmost importance to utilise and integrate different NDT techniques for overall health monitoring.

1.2 Motivation and Research objectives

1.2.1 Motivation
Structures are composed of a variety of construction materials such as metals, alloys, concrete, masonries, polymers, fibre composites, timber and glasses [8]. The NDT technique for these diverse materials should be chosen on the basis of [9]:

a. The physical nature of the material property or the discontinuity
b. The underlying physical process that governs the NDT methods
c. The physical nature of the interaction of the sensor with the test material
d. The economic, environmental and other factors

The material properties can be differentiated into mechanical properties and electromagnetic properties. The mechanical properties are hardness, compressive strength, elasticity, ductility, tensile strength and elastic constants. The electromagnetic properties are conductivity, permittivity and magnetic permeability. Further, several discontinuities/damages such as voids, cracks, debondings, delamination also affect the characteristic properties of materials. For instance, crack
in metal has different property compared to crack in the concrete. The diversity of the structure is not only limited to the material property but also the geometrical shape which also influences the sensitivity of different sensors used in these NDT techniques. The diverse material properties, geometrical shapes and varied damages in the structures make the selection of NDT technique a challenging task. The potential and limitations of each NDT technique should be considered based on the material property. Also, it is impossible to use a single NDT technique for different construction materials in a structure. Based on this status quo, a combination of different NDT techniques or the development of an integrated NDT technique can overcome this current limitation. This study focuses on the use of such combination of NDT techniques and integrated NDT techniques for health monitoring of a variety of construction materials with a variety of damages. These construction materials include concrete, metals and polymers which are most abundantly used in civil infrastructures. The damages include both surface and hidden defects including cracks, cuts, blowholes, gaps and debondings.

1.2.2 Research Objectives
The primary objective of this research is to develop a methodology for non-destructive testing of construction materials and structures with microwave, laser and piezoelectric sensing techniques. All of these techniques are proven NDT method with their advantages and limitations explained previously. We aim to utilise the advantages of these popular techniques and combine the methodology to address the limitations of the individual technique. Based on the different properties of materials under test, these techniques are applied either separately or simultaneously for their investigation. Further, we aim to develop a novel imaging sensor system for SHM by integrating microwave and laser sensor techniques to utilise the benefit of these techniques and their combination for SHM applications in demand. This system will be able to generate high-quality microwave images of construction materials providing automated control of the movement of a microwave antenna over the specimen under investigation using the laser displacement sensors. The objectives of this research work can be divided into general and specific objectives. The general objectives of this research are as follows:
• To develop a laser displacement sensing technique and methods for profiling and non-destructive evaluation of surface flaws in civil infrastructures;
• To develop a methodology for microwave imaging of tilted construction materials and structures;
• To develop a compact wireless microwave imaging system that acquires microwave data through the wireless link;
• To develop a novel dual laser integrated microwave imaging system and software by combining laser and microwave sensing techniques to provide contour following and optimisation of the standoff distance between a microwave antenna and the non-plain structural components;
• To develop a piezoelectric sensing technique for non-destructive evaluation of gaps and debondings between external reinforcement and concrete.

To achieve the general objective and to prove the applicability of the developed system, the research work can be sub-divided into the following specific objectives:

• One-dimensional profiling and crack detection in metals, polymers and concrete specimens using the developed laser displacement sensing system.
• Two-dimensional profiling and cut/crack detection in metals and concrete specimens using the developed laser displacement sensing system.
• Hidden target detection in composite materials using the developed microwave imaging system.
• Surface and hidden hole and crack detection in plain and tilted metal specimens using the developed microwave imaging system.
• Surface and hidden crack detection in plain and tilted concrete specimens using the developed microwave imaging system.
• Hidden target detection in composite materials using the developed wireless microwave sensing system.
• Cracks/Gaps detection in complex shaped metal and concrete specimens using the developed dual laser integrated microwave imaging system.
• Debondings and gaps detection in concrete based composite materials using the developed piezoelectric sensing technique.
1.3 Major Contributions

In this thesis, the methodology of three different NDT techniques namely, microwave imaging technique, laser sensing technique and piezoelectric sensing technique has been developed. These different techniques have been used as a stand-alone method and as a combination for investigating various construction materials and structures. For the combination method, a novel dual laser integrated microwave imaging system was developed and used for NDT of diverse construction materials with varied geometrical shapes.

The major contributions and their brief descriptions are as follows:

- **Laser displacement sensing and imaging system for profiling and surface crack detection in a variety of construction materials and structures**
  A novel algorithm was developed, and software/GUI was developed on the LabVIEW platform that performed one-dimensional profiling and cracks detection in concrete. Further, the software was improvised for two- and three-dimensional imaging and flaw detection in a variety of plain and non-plain construction materials and structures.

- **Methodology for the detection of various flaws in tilted and non-tilted cement based infrastructure materials using microwave imaging system**
  An algorithm was devised, and software/GUI was developed on the LabVIEW platform to use the existing microwave imaging system for the tilted specimen.

- **Compact wireless microwave sensing system for spot measurement by using a wireless link for data acquisition**
  A compact wireless microwave imaging system was developed by replacing the wired data acquisition modules with a wireless link. The proof-of-concept of the system was given by performing spot measurement in different specimens.

- **Development of dual laser integrated microwave imaging system**
  A novel dual laser integrated microwave imaging system was developed. This included hardware design, algorithm development and software/GUI
development. The developed system was used for NDT of tilted and non-plain infrastructure materials. Further, comparison of different microwave antennas was performed to use with a variety of construction materials.

- Methodology for piezoelectric sensing technique for a novel application of gap and debond detection between external reinforcement and concrete
  A piezoelectric sensing technique was used for the gap and debonds detection between various external reinforcements such as metals and CFRPs, and concrete. Various damage indexes were proposed using different statistical parameters.

1.4 Publications
Following research papers are published or submitted in peer-reviewed journals or conference proceedings:

**Journal Papers:**


**Conference Papers:**


1.5 Thesis Organisation

The remainder of the thesis is organised as follows:

- Chapter 2 provides a comprehensive literature review on different sensing techniques for non-destructive testing of construction materials and structures. A detailed description of techniques that are focused on this study such as microwave and millimetre wave NDT technique, laser displacement sensing techniques and ultrasonic techniques and their advantages and limitations are provided. Further, a brief description of other popular NDT techniques such as visual inspection technique, acoustic emission technique, thermal imaging method, fibre optics method and different laser sensing techniques is given. The issues limiting the real-life application of current microwave and millimetre wave techniques are foregrounded. Further, the necessity of using integrated NDT techniques to fill this research gap is highlighted. The comparison between wired and wireless sensor networks for NDT is made, and the advantage of wireless technique over wired technique is illustrated.

- Chapter 3 presents a novel laser displacement sensing system developed for surface profiling and imaging of a variety of infrastructure materials for surface flaw detection irrespective of their material property. Background on the need for a simple, robust and cost-effective NDT technique such as the proposed laser displacement sensing system is provided. A detailed methodology for the system development and uncertainty analysis of the measurement technique is given. Two different systems were developed based on laser displacement sensors, namely, one-dimensional profiling and flaw detection system, two- and three-dimensional imaging and flaw detection system. The developed system was utilised for profiling and surface flaw detection in different specimens based on materials such as metal, dielectric and cement-based material. The analysis of the result and analysis of the flaw detection capability of the developed system is discussed.
• In chapter 4, a detailed description of the development of the microwave imaging system for plain and tilted specimens are provided. A foundation on microwave non-destructive technique with a focus on near-field measurement technique is given. The development approach of the imaging system with an explanation of each module is explained in detail. These modules included signal generation and data acquisition module, a scanning module, and control and visualisation module. The developed system was applied for non-destructive testing of metals, metal-based composites, cement based specimens and dielectric specimens. The imaging results of these specimens are presented, and a detailed analysis is performed. Next, a wireless microwave sensing system was developed by replacing the wired connection between microwave detector and the base station and the system was implemented for spot measurement applications.

• Chapter 5 presents a novel dual laser integrated imaging system. The imaging system was developed to fill the research gap explained in chapter 2 and 4. The developed system utilised laser displacement sensors and microwave sensors for investigation of the structure with complex geometrical shapes and curvatures. The detailed description of each module of the developed system along with the algorithm for development and synchronisation of these modules is demonstrated. The comparison between dielectric waveguide antenna and open-ended waveguide antenna were performed to find the suitable antenna for the proof-of-concept of the developed system and then used with the developed system to detect flaws in a variety of construction materials such as metals and plasterboard. Finally, the summary with the discussion of the results is given, and suitable antenna for non-destructive testing of non-planar structures is recommended.

• In chapter 6, a methodology for monitoring interfacial defects such as debondings and gaps between different materials in structures such as metal-concrete gap, the CFRP-concrete gap is given. The methodology is based on piezoelectric sensing technique. Further, this technique is used to detect gaps
between CFRP plate and an early age as well as hardened concrete. The advantage of proposed piezoelectric technique over conventional technique for debonding and gap detection is provided. The measurement and statistical results are presented which proves the applicability of the technique for detecting interfacial defects in real-life structures such as concrete-filled steel tubes and CFRP reinforced bridge structures.

- Investigation summary and conclusions based on the research outcome of the thesis is provided in Chapter 7. Furthermore, recommendations for future work related to the continuation of the research and development are also presented.
Chapter 2 Literature Review

2.1 Overview
The literature review firstly introduces the non-destructive testing (NDT) techniques and their use in civil infrastructures in Section 2.2. Secondly, some of the commonly used non-destructive testing techniques are reviewed in Section 2.3. Then, different wired and wireless sensor networks for NDT are reviewed in Section 2.4, and finally, the summary is given in section 2.5.

2.2 Non-destructive testing
Structural health monitoring (SHM) is an emerging field that has received considerable attention in recent years especially in the areas of mechanical, aerospace and civil engineering that are directly associated with people’s lives and property. Thus, a multidisciplinary approach among these subject areas is needed for SHM as it encompasses not only non-destructive testing and evaluation of structures but also includes structural dynamics, fatigues and fractures, signal processing, sensors and actuators, wireless systems and many other disciplines. The term SHM is vast and has been described by various authors in various ways. According to Balageas, et al. [10], structural health monitoring is a diagnosis technique of the state of each material of each part as well as the complete structure itself. Sohn, et al. [11] define SHM as an implementation process of a damage detection strategy for aerospace, civil and mechanical engineering infrastructures. Farrar and Worden [12] explain the process of SHM as the observation of structure over time with periodic measurements, extraction of damage sensitive features from these measurements and the statistical analysis of these features to determine the health of the structure. Giurgiutiu [13] explains that SHM assesses the state of structural health and can also be used to predict the remaining life of structure using appropriate data processing and interpretation techniques. Staszewski, et al. [14] highlight that SHM is a safety issue as structural health is directly related to structural performance which is one of the major parameters to be considered for the safety of operations. In our context, the definition from Farrar and Worden [12] holds mainly because our research work is focused on
measuring the damage sensitive features over time and analysis to determine the health of the structure.

Non-destructive testing (NDT) also referred to as Non-destructive evaluation (NDE) or Non-destructive Inspection (NDI) is a subdivision of SHM that focuses on critical components of a structure and is used for localisation and evaluation of defects [15]. Defects such as cracks are a local phenomenon and may not have a significant influence on the global behaviour of the structure and in such cases, NDT is the only viable method for monitoring these structures. NDT is a broad group of analysis technique used to evaluate the properties of a material, component or system without causing damage. It is a technique that is based on the application of physical principles employed to determine the characteristics of materials or components or systems and for detecting and assessing the inhomogeneities and harmful defects without impairing the usefulness of such materials or components or systems [6]. NDT focuses on critical components of a structure and is used for localisation and evaluation of defects. Defects such as cracks are a local phenomenon and may not have a significant influence on the global behaviour of the structure. In such cases, NDT is the only viable method for monitoring these structures and knowledge of critical areas of a structure is needed as it will facilitate the inspection process of complex structures [16].

Recent advancement in NDT techniques has provided an independent approach for detection and assessment of the condition of the structures by providing us with real-time data of damage, thereby saving considerable time and cost [17]. The lack of proper NDT techniques has caused enormous damage to property and lives. Some of the examples of these unfortunate events are Nicoll highway collapse in Singapore on 20th April 2004 (c.f. Fig. 2.1a) which resulted in human casualties as well as enormous loss of property [18]. The main reason for the collapse was sway failure of the strut-waler connection. Similarly, Sampoong department store collapse in South Korea on 29th June (c.f. Fig. 2.2b), 1995 killed more than 500 people and injured thousands with more than 200 million USD property damage [19]. The primary cause of the collapse was reduced slab depth and excessive loads. Preliminary indication of failure such as cracks were present which were neglected causing the failure of the entire structure [20]. The above two cases are few of the examples of the fatal incidents that happened
because of the absence of proper NDT techniques and lack of regular monitoring of structures [18, 19]. Utilising proper NDT techniques for constant monitoring of structures could have given early warning signs enabling proper precautionary measures.

For different engineering structures and different engineering disciplines, the approach of NDT might be different. However, the main idea behind all these NDT techniques remains the same as each NDT process involves data acquisition, signal processing and analysis. Fig. 2.2 shows a typical architecture of an NDT system which consists of a sensing unit, data acquisition unit, communication network, and data management and monitoring unit. Sensing unit includes sensors interrogating the structure. Data acquisition unit consists of a signal conditioning circuit, analog to digital converter, timing circuits and data storage devices. Data management unit consists of data storage devices, data analysis and monitoring section. The communication network is responsible for data transfer between these data acquisition and data management unit.

**Figure 2.1:** Examples of failures of civil infrastructures due to the lack of IHM techniques (a) Nicoll highway collapse and (b) Sampoong department store collapse.
NDT has an advantage over conventional destructive tests in many aspects. The ability to test the structural parameters without the need for damaging is the main advantage of the NDT over the destructive testing approach. Table 2.1 lists the advantage and limitations of NDT over destructive testing. However, the advantage of NDT far outweighs the limitations and has evolved as the most popular technique for damage detection and material evaluation.

Table 2.1: Comparison of destructive and non-destructive tests [6]:

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<tr>
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<th>Destructive tests</th>
<th>Non-destructive tests</th>
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<tr>
<td><strong>Advantages</strong></td>
<td>1. Tests cannot be made on the structure directly, and the correlation between the sample specimens and the real structure needs to be proved.</td>
<td>1. Tests can be made directly on the structure or any structural components.</td>
</tr>
<tr>
<td></td>
<td>2. A single test may measure only one or a few of the properties of any material or structure.</td>
<td>2. All properties of the material and structure can be identified using multiple NDT techniques.</td>
</tr>
</tbody>
</table>
In-service testing is not possible as the structure needs to be destroyed.

Measurement of properties of the material over a cumulative period cannot readily be possible.

The time and expense required to prepare the test specimen are generally high.

Measurements are highly reliable as the correlation between test measurements and material properties are direct.

Measurements are usually quantitative.

NDT in civil infrastructures has transitioned from research to practice with the development of new technologies and algorithms. This initiation has mainly been driven by significant infrastructure developments such as the oil industry, operators of large dams and highway agencies [21]. Contrary to mechanical and aerospace industry, a considerable challenge in developing NDT technique for civil infrastructures is the uniqueness of each structure which has no baseline as in mechanical and aerospace structures. However, NDT in civil infrastructure is of utmost importance, and the technology is growing in recent years with the advent of new techniques and methods.
2.3 Commonly used NDT techniques

NDT can be performed on a variety of construction materials such as conducting materials, dielectric materials or composite materials that constitute a structure. Common NDT techniques include ultrasonic, thermographic, optical, electromagnetic, magnetic particle, liquid penetrant, radiographic, remote visual inspection, eddy-current testing and low coherence interferometry [22]. NDT methods rely upon the physical nature of the material property or defects and the understanding of the underlying physical process of the method itself. Further, the methods rely upon the physical nature of the interaction of the sensor with the material under test [9]. The selection of NDT technique depends on factors such as the type of materials and its dimensions, the environment, the positions of interest within the structure under investigation and the suitability of data acquisition and processing. A combination of two or more methods is generally required for the complete inspection of a structure, but it does not imply that they may be regarded as alternative techniques. In most cases, one of the methods is used to complement another or to verify the finding of the other [23]. Some of the commonly used NDT techniques with their advantages and limitations are reviewed below:

2.3.1 Microwave and millimetre wave NDT techniques

Microwave and millimetre waves are electromagnetic waves which have been applied in multiple fields and are a viable solution for NDT of different structures. Microwave frequency spectrum ranges from 300 MHz to 30 GHz while millimetre wave frequency ranges from 30 GHz to 300 GHz [24]. The waves at these frequencies can penetrate and interact with the inner structure of dielectric materials making them a valuable asset for damage detection in these materials. The application of these techniques include dielectric material characterisation [25], inspection of layered structures with detection of debonding, delamination and corrosion [26-29], surface crack detection, crack sizing and imaging of defects on the surface as well as inside the dielectric structures [30]. Microwave and millimetre wave inspection techniques were also used to detect rust under paint and composite laminates [31], to determine the physical properties of cement-based materials [32], to measure dielectric properties of composite sheets [33], to detect fatigue cracks in metal [34, 35], to analyse ageing
effect and quality control of mortar specimen [36] and to evaluate depth of shallow flaws in metals [37].

One of the microwave and millimetre wave NDT techniques consists of a reflectometer with microwave antenna and conditioning circuit. A reflectometer is a microwave circuit which can transmit microwave signal at a particular frequency and polarisation and is also able to receive the reflected signal [38]. The output from this reflectometer is proportional to the magnitude and phase of the reflected signal. Fig. 2.3 shows the schematic of dual-polarised microwave reflectometer used to detect debond and delamination in Carbon Fibre Reinforced Polymer (CFRP) strengthened composite structure.

![Figure 2.3: Schematic of the inspection system with dual-polarized microwave reflectometer.](image)

Microwave and millimetre wave imaging is performed by scanning a single antenna over an object or using an antenna array. Further, algorithms such as synthetic aperture radar (SAR) utilises the amount of phase change in the medium (object) as the signal travels through it to synthetically focus the electromagnetic beam at a certain distance from the antenna. Then, SAR images can be produced from the raw image by coherently summing up reflected signals obtained over a 2-D scanned area [39, 40].
simplest microwave imaging systems consist of a transmitter, receiver (detector) and an antenna. Generally, a network analyser with a capability of both microwave signal generation and data acquisition is used as a transmitter/receiver while a computer is used as a control centre and signal processing unit to generate and visualise the image. Microwave imaging system is capable of generating images of the surface as well as the internal structure of the non-conducting materials. For imaging purposes and when operating in the near-field region of open-ended probes, the spatial resolution is determined by the probe aperture dimensions, which are relatively small at the microwave frequency ranges.

**Figure 2.4:** Microwave imaging using reflectometer: (a) setup of a 2-D scanning mechanism for tilted CFRP-mortar sample, (b) image of debonding in CFRP-mortar sample, (c) setup of a 2-D scanning mechanism in the abutment of a bridge and (d) image of the debond in bridge abutment.

Scanning is a vital part of any microwave imaging system and depending upon the need; various scanning patterns can be utilised [41, 42]. During the scanning, the
distance between the open-ended probe and the surface of the test specimen which is called standoff distance plays a vital role. In an ideal condition, the standoff distance should be constant to obtain a non-varying signal from the probe which will result in better images. However, the standoff distance may change in real life scenarios because of several conditions such as relative tilting between probe and specimen, shaking or vibration of either a probe or a specimen or both, surface roughness and irregularities. This change in standoff distance may cause small abnormalities such as minute cracks, delaminations or debonding to remain hidden during the inspection as the property of the received microwave signal might change. Several research works have been undertaken in the past to optimise this standoff distance with some good results. However, some techniques are contact-based methods which are not practical in non-contact sensing application while some require post-processing which is time-consuming and impractical in real life scenarios. Similarly, other techniques are capable of adjusting the standoff distance on only linear tilts such as ramps [39, 42]. For example, Fig. 2.4 shows the setups, and the microwave images of the debond in tilted CFRP strengthened mortar sample in the laboratory and CFRP-strengthened concrete members in an actual bridge [42]. The standoff optimisation was done in the laboratory sample as shown in Fig. 2.4 (The images show a good indication of debonding in both cases (c.f. Fig. 2.4b and 2.4d).

Advantages of near-field microwave and millimetre wave technique [43]:

1. Non-contact nature of measurement.
2. Ability to penetrate inside dielectric material.
3. Low-power consumption.
4. Robust and compact design.

Limitations of near-field microwave and millimetre wave technique:

1. Not able to penetrate inside conducting material.
2. Standoff distance change during scanning masks the indication of minute flaws.
3. Not able to image structure with different geometrical shapes and curvatures and only able to image plain tilted specimens.
2.3.2 Laser displacement sensing techniques

Laser sensing techniques are growing at a rapid pace with the advancement in technology, and its use in NDT has also seen widespread growth. The non-contact nature of laser makes it a feasible technology for long-term inspection as it causes no damage to soft specimens and is equally applicable in high temperatures as well as electrically active specimens. One of the popular laser sensing techniques used in NDT is a laser displacement sensing technique.

The laser displacement measurement technique is a method of measuring displacement value to detect damages in infrastructure. Laser Displacement Sensor (LDS) is a displacement detecting tool that gives the output based on the distance of an object from the sensor head. It uses a laser beam to measure distance in a non-contact mode. An LDS is an economical solution to monitor the condition of a structure as a single LDS can be used to monitor multiple structures. The non-contact nature makes it viable for remote health monitoring. LDS works on laser triangulation principle which generates an output voltage at every laser spot on the surface of the target. This output voltage can be converted to corresponding displacement reading. Fig. 2.5 shows the schematic of laser displacement sensing reported by [44] which utilised the triangulation principle for displacement measurement.

Figure 2.5: Schematic of laser displacement sensing using the triangulation principle [44].

LDS was used to monitor blade deflection in wind turbine blades caused by nacelle tilting [45, 46]. It was also used to measure vertical displacements of the main
structural member of a building under construction [47]. Further, LDS was used for the real-time gauge measurement of rail tracks [44] and the rail profiles [48]. Defect detection in metallic plates was performed using LDS and modal analysis technique [49, 50]. Displacement value obtained from LDS was correlated with stiffness using different training models in joint connection of a frame structure by monitoring the vibration [51]. Displacement measurements have been used in several other applications related to health monitoring, in particular for measurement of surface roughness and/or profile of a structure. For instance, LDS was used to determine the smoothness of wood and to measure different profiles for different wood species [52].

Terrestrial laser scanning (TLS) techniques also make use of displacement measurement. However, this technique is more focused on larger targets over large surface areas and uses bulky instrumentation system. This method is applicable for shape detection as well as large defects in structures. A typical example of a terrestrial laser scanning technique is shown in Fig. 2.6 which was used for 3-D characterisation of the fracture system of a basement structure [53]. 3-D Laser Survey System was used to measure the displacement in a building wall caused by fire and tracking laser was used to measure the displacement of a building under wind loading and also at different temperature conditions [54]. Similarly, TLS technique was used to detect cracks wider than 1-cm in width which can occur on infrastructures like roads [55]. TLS measurement was also used to determine the shape of simply supported beams in a three-dimensional image form [56].
The advantages of laser displacement sensing techniques are as follows [57]:

1. Non-contact nature of measurement.
2. Full-field view of the target area can be examined and measured.
3. No additional accessories like penetrants, coating or marking materials are needed.
4. Flexible range of measurement.
5. Real-time measurement of the specimen is possible.

The limitations of laser sensing techniques are as follows [22]:

1. Special safety consideration must be taken when using lasers.
2. Bulky instrumentation system needed for TLS.
3. Data interpretation is difficult in TLS where the size of data is large.
4. Slight correction may be needed for determination of the location of defects.
5. Only surface health monitoring of opaque materials is possible.
6. The measurement parameters in an outdoor environment may need to be adjusted based on environmental conditions such as rain or fog.

### 2.3.3 Ultrasonic techniques

Ultrasonic technique is a damage detection technique that makes use of an ultrasonic wave by passing through the test material. This ultrasonic wave generated using a
transmitter is either reflected or mode converted by any defect, discontinuities or flaws in the material which is picked up by a receiver. The received signal is then used to analyse any defect or deformity condition. The conventional linear ultrasonic method uses phase velocity and amplitude attenuation measurements for damage monitoring of civil structures. However, guided waves are also being used which utilises dispersion effects and multimode propagation [57]. Generally, the ultrasonic method consists of transmitter and receiver on opposite surfaces of the material to be tested to realise transmission through sensing. In other methods, transmitter and receiver are placed on opposite sides of the interrogation area on the same surface known as ultrasonic pitch-catch technique. The method might also consist of a single transmitter/receiver transducer which works in a pulse-echo mode [58]. The transducer is generally piezoelectric which is able to send and receive mechanical vibrations. Materials with piezoelectric properties are able to convert electric pulses to mechanical vibrations and vice versa and generally consist of a plate of polarized ceramic or crystalline material with electrodes on the opposite surfaces [22]. Fig. 2.7 shows the schematic diagram of air-coupled pitch-catch ultrasonic technique reported by Delrue, et al. [59] which used two air-coupled ultrasonic transducers, one for the excitation and one for the sensing purpose. In some cases, the laser has also be used as a non-contact ultrasonic generator [60] and Laser Doppler Vibrometer (LDV) as ultrasonic sensor [61, 62].

The ultrasonic method has been used for NDT of various defects in aircraft structures [63-65], defects in welding [66, 67], defects in composite structures [60, 62] and defects in concrete [68].
The advantages of the ultrasonic method are as follows [69]:

1. Able to detect microcracks with reasonable accuracy.
2. Localisation technique is useful in detecting defects.
3. Some level of penetration inside conducting material.

The limitations of the ultrasonic method are as follows:

1. Need for high power to generate a signal.
2. False alarms due to embedded sensors and coupling materials.
3. Difficulty in detecting flaws in non-conducting materials such as concrete.

2.3.4 Other NDT techniques:

Besides the above NDT methods, several other NDT techniques are being used. Some of these techniques are visual inspection technique, acoustic emission technique, thermography, fibre optic technique, x-ray technique and so on. The brief description of some of these techniques are given below:

2.3.4.1 Visual inspection technique

Visual inspection is the most common and traditional form of NDT. The visual inspection includes not only direct inspection using the naked eye but also requires additional visual treatments during the examination for the interpretation of images.
Thus, the basic procedure used in visual NDT involves illumination of the test specimen with light, then an examination of the test specimen with either eye, light sensitive devices such as photocells or by using a camera. Visual inspection can provide a good summary of the condition of damage but fails to detect localised damage effectively and requires extensive preparation which might take a long period and in structures like bridges, this might lead to closure during the inspection period [71]. Due to these factors, visual inspection cannot be an accurate measure for damage detection exclusively and can only be used as a preliminary investigation tool. Visual inspection method may also include audio inspections by impacting a structural member by a hammer to detect piping and hollowness in timber structure such as timber electricity poles and timber bridge girders.

2.3.4.2 Acoustic emission technique

Processes such as cracking, debonding, delamination, deformation are directly related to the health of a structure and produce a localised transient change in stored elastic energy with wide spectra [58]. This wave of energy is called acoustic emission (AE) and can be recorded by sensors and analysed to extract information about the source of emission. These mechanical waves are detected and converted into electrical signal, mainly by using surface-mounted piezoelectric sensors. However, embedded piezoelectric sensors, piezoelectric composite materials, thin film sensors and optic-based sensors can also be used as detection sensors [72]. Fig. 2.8 shows the principle of acoustic emission method reported by Nair and Cai [73] where external stimulus is used to generate mechanical waves which are recorded by one or more sensors and sent to the electronics which consists of the signal processing unit.
AE technique has the advantage of detecting and locating cracks in one measurement, and the propagation of an acoustic wave through the structure makes it possible to detect damage in inaccessible areas and with a minimum number of sensors. Also, AE can passively monitor the dynamic reaction of the test specimen when the load is applied without any interference [22]. However, the limitation of this technique is that the background noise can affect monitoring in large structures. Also, to cover large areas, a large number of sensors is needed which ultimately increases the number of data and thus takes considerable signal processing time. AE technique has been used in monitoring fatigue crack developments in steel structures [74]. Also, cracks in concrete due to the fracture mechanism using AE sensors were investigated [75].

2.3.4.3 Thermal imaging method

Thermography or thermal imaging is a defect detection technique of using thermographic or infrared cameras to produce the image of radiation detected in the infrared range owing to temperature difference on the investigated surface. This method can be divided into passive or active method based on the technique of thermal excitation. In the passive method, the structures or materials to be tested are naturally at different temperatures than the ambient temperature while in the active method, an external source such as lamps or hot/cold air guns is used to provide thermal contrast between the test material and external surrounding [76]. Passive thermography is mainly applicable to NDE in buildings, components and properties evaluation. Active thermography can further be divided by various thermal stimulation methods. Some of the types of active thermography are pulsed thermography, lock-in thermography,
vibrothermography and step heating thermography [77]. In pulsed thermography, heat stimulation is provided by xenon flash lamp or halogen lamp. In lockin thermography, the heat stimulation source depends on the material to be tested. For example, in composite materials, the heat source can be halogen lamps, ultrasounds or even mechanical excitation. In vibrothermography, the heating is mainly done by using external mechanical vibration while in the step heating thermography method, halogen lamps as well as lasers can be used for heating the test material [76, 78]. Fig. 2.9 shows the schematic of the principle of active thermography measurements where the heat source was provided by the radiator and an infrared camera was used as a detector [79].

**Figure 2.9:** Schematic of the principle of active thermography measurements [79].

The advantage of thermal imaging method includes its non-contact feature, fast inspection rate for large areas, easy interpretation of thermographic images and broad applications. Also, it is a risk-free technique without any emission of harmful radiation. The limitations include expensive equipment, inability to penetrate thick specimens, thermal losses and difficulty in stimulating large areas uniformly. Thermal imaging method has been used for monitoring welds [80-82], concretes [83] and aircraft [84, 85].

### 2.3.4.4 Fibre optics method

Fibre optic sensors are lightweight and durable sensors for NDT. These sensors are either glass or plastic fibres designed to guide light along its length. Fibre optic sensors...
are capable of sensing a variety of perturbations and are mainly used to sense temperature and strain. There are mainly four types of fibre optic sensors. Point sensor with single measurement point, a multiplexed sensor with multiple measurement points, long-base or long-gauge sensors which measure over a long measurement base and distributed sensors which can measure at any point along the length of the fibre [57]. These sensors are mainly based on three sensing mechanisms namely, intensity, wavelength and interference of the light wave [1]. Fibre Bragg Grating (FBG) and interferometric sensors are based on wavelength or frequency [86, 87]. Brillouin scattering, as well as intensity modulation of lightwaves, have also been used for NDT [88, 89]. Among these sensors, the Fabry–Perot fibre optic sensor and the long gauge are the two types of local sensors commonly utilised in civil engineering [5]. Fig. 2.10 shows the functional principle of Fabry-Perot fibre optic sensor which constitutes a capillary silica tube containing two cleaved optical fibres with an air gap between them [90].

![Figure 2.10: Functional principle of Fabry-Perot fibre optic sensor [90].](image)

The advantage of fibre optics sensors is its durability, stability and insensitiveness to external interferences. They can be used in a large number of applications of NDT in an extensive range of structures. They can either be used as a link between sensor and signal conditioner or can be used as a sensor itself [57]. Further, these sensors are immune to any electromagnetic interference and can be multiplexed to cover a large area. The limitation of fibre optic sensor is its cost and a need for highly trained professionals. Fibre optics sensors are used in the monitoring of concretes [88, 89], aircraft [91], welds [92] and railways [93].
2.3.4.5 Eddy current method

Eddy current method utilises the electromagnetic induction phenomenon where a conductive structure is subjected to a time changing magnetic field for identifying defects [94]. When an alternating current is used to excite a coil, an alternating magnetic field is produced such that the magnetic lines of flux are concentrated at the centre of the coil. For defect detection, this coil is located at a small distance from the conductive structure to be tested. The alternating magnetic field penetrates the structure and generates eddy currents. The magnitude and phase of this eddy currents affect the impedance of the coil. Any defect on the structure impedes the flow of eddy current and lengthens the eddy current path which reduces the eddy current density and leads to change in the coil impedance. Therefore, when a coil is moved over a defect at a constant rate and a constant standoff distance, the structural integrity and the location of damage could be identified by detecting a momentary change in the coil reactance and coil current [22]. The basic principle of eddy current method is given in Fig. 2.11 [95].

![Figure 2.11: Schematic of a coil excited by an alternating current (I) and showing the direction of primary (H) and secondary (B) magnetic fields and induced eddy currents (EC) in a test material.](image)

The eddy current method is readily applicable to conducting materials such as metals. The method is entirely non-contact and does not require surface preparation for the test. The technique is economical, portable and highly sensitive to different geometric and material parameters. However, the high sensitivity can be a limiting factor where considerable information increases complexity. One of the primary limiting factors of
this method is the inability to detect defects in non-conducting materials like concrete. Further, the method is only sensitive to defects perpendicular to the interrogating surface [9]. Eddy current method is used in the detection of corrosion in metal plates [94, 96], fatigue cracks in bolt holes [97], defects in underground pipes [98] and measurement of thickness in metal plates [99, 100].

2.3.4.6 Other laser sensing techniques

Besides, laser displacement sensing technique, other laser sensing techniques used in NDT are as following:

a. **Laser interferometry**: Laser interferometry makes use of superposition principle to combine light waves and detect any abnormality in the target surface by determining the original state of the light wave. The interferometer used for this purpose can be amplitude-splitting such as Fabry-Perot, Michelson and Mach-Zehnder interferometers or wavefront-splitting such as Rayleigh and Fresnel interferometers. The decision to use different kinds of interferometers depends on the target surface. For a smooth surface, amplitude-splitting interferometers can be used because of the absence of any speckle while for a rough surface, wavefront-splitting interferometers can be used which takes into account the formation of the speckle pattern. The interferometers usually consist of the laser as a light source, beam splitters and beam expanders, mirrors and image recording devices or photodiodes such as charge-coupled device (CCD) [57].

![Figure 2.12: Schematic of the single-probe interferometer [101].](image-url)
Dual probe interferometer was developed by taking the reference of single probe heterodyne interferometer. Combinations of acousto-optic modulator (AOM), beam splitters, mirrors and photodiodes were used for the detection process as shown in Fig. 2.12 [101]. This interferometer system was used to monitor an aluminium plate. Bruttomesso, et al. [102] used broadband laser interferometer to measure the effect of piezoelectric transducers which are commercially available. Parameters such as sensitivity, repeatability and frequency response of each transducer generating acoustic emission were examined. Similarly, laser interferometer was used for sensing high frequency guided ultrasonic wave to detect fatigue cracks in fastener holes of an aircraft [103]. Laser interferometer was also used to measure the velocity of vibration of the building caused by air movement [54].

b. **Laser shearography**: Laser shearography is also similar to interferometry, but its technique is based on image shearing principle where two angularly separate beams are obtained after the light beam is split when passed through a refractive prism. These split beams, which are not parallel to each other, are then passed through image shearing device to make them collinear. The resulting low spatial frequency is passed through image recording devices or photodiodes such as CCD which produces an image. The image from the surface at rest is then compared with an image of a loaded or excited surface to produce a fringe pattern which is then enhanced and analysed using different software [22, 57]. Fig. 2.13 shows the functional diagram of the operation of laser shearography.
Laser interferometer was used for the defect detection in composite structures using shearography technique. A ruby laser was used as a light source to illuminate the test surface, and a CCD camera was used to record the interference pattern [104]. Multi-wavelength speckle pattern shearing interferometer was used for measuring strain in aluminium block using three diode laser [105].

c. **Laser scanning photogrammetry:** Photogrammetry is the process of deriving the shape and location of an object by interpreting the image taken of that object. Photogrammetric measurement is 3-dimensional (3-D) representation of an object in the digital or graphical form [106]. Laser scanning photogrammetry is an integrated technique which combines laser scanning and digital photogrammetry where the laser is used to scan over the object surface. The reflected beam is captured by a digital camera, and the 3-D image is regenerated for further analysis. Fig. 2.14 shows the schematic of laser scanning photogrammetry where laser beams are directed along a 2-D line.
The photogrammetric measurement was used to monitor vertical bridge deflection and was compared with finite element analysis results [107]. Similarly, this method was used to monitor large wind turbines of up to 80 m in diameter [108]. Photogrammetric modelling procedure was used to analyse the timber roof of a building [109].

d. **Laser doppler vibrometry**: Laser Doppler Vibrometer (LDV) is a non-contact velocity transducer based on the analysis of Doppler effect on the laser beam emerging from a solid surface [110]. LDV technique provides high sensitivity and automated method for IHM. In this technique, a laser beam illuminates the surface of a target which is reflected. The reflected beam is combined with a reference beam which has a different frequency. This frequency shift is related to the instantaneous velocity of the target due to the Doppler shift which is used for coherent detection. The LDV method can be combined with several methods of excitation like impact hammers [111], ambient effects [54], laser pulses [112] or electrodynamic shakers [113]. LDV can detect the change in velocity or vibration from all these excitation sources. Fig. 2.15 shows the schematic of the LDV system reported by Martarelli, et al. [110] with the optional Bragg cell and Electronic mixing unit.
Mallet, et al. [114] used a piezoceramic transducer as an actuator in the rectangular aluminium plate to generate Lamb waves. Scanning laser vibrometer was used for sensing purpose. The scanning head launched a probe beam to the surface of the analysed specimen that collected the back-scattered light signal to detect damage in aluminium plates and also fatigue cracks in metallic structures [114-116]. LDV technique was used with ambient vibration source for the vibration-based damage detection in steel structures [117]. Castellini and Santolini (1998) used LDV to analyse the vibration behaviour of naval propeller rotating in water [118].

**Figure 2.15:** Schematic of a Laser Doppler Vibrometer system [110].

![Schematic of a Laser Doppler Vibrometer system](image)

**Figure 2.16** shows the schematic of ultrasonic wave propagation imaging system
reported by Lee, et al. [119] used in a nuclear power plant pipeline where the laser is used as an ultrasonic generator aided by laser mirror scanner (LMS) while the ultrasonic sensor is attached to the pipe.

Figure 2.16: Schematic of ultrasonic propagation imaging system using a laser as an ultrasonic generator [119].

Laser ultrasound technique was used to detect manufacturing flaws and debonds in composite structures [121, 123], damage in nuclear power plant pipelines [119], damages in wind turbine blades [122, 124], hidden cracks and impact damage in metal [120] and to detect cracks in hot aluminium plates [125].

2.4 Wired and wireless sensor networks for NDT
NDT involves inspection and monitoring of structures over a long period. The data from the sensors need to be collected and analysed continuously for efficient monitoring. Further, multiple sensors are needed to cover large structures like bridges, towers or buildings. For this purpose, multiple data need to be acquired through multiple channels simultaneously. The use of wires/cables between sensors and monitoring stations for this purpose is a conventional and most widely used approach
However, the drawbacks of the wired system include the high cost of wiring, disturbance to the normal operation of the structure due to wiring all over the structure, high cost of equipment and the high cost of maintenance [127]. To overcome this limitation, the research scientists are actively exploring new technologies that are capable of advancing existing technology in structural monitoring [16]. Wireless sensor network (WSN) is one such technology that is capable of meeting the need of state of the art, is economical and convenient monitoring technology. The use of wireless technology makes it possible to install hundreds of sensors in the structure without the need for wasting time, money and effort to connect wires for the entire sensors individually. During the design of wireless sensor networks, features such as power consumption, accuracy, analog-to-digital conversion precision, local data processing capability, peer to peer communication between each sensing unit are essential and need to be considered carefully [126].

WSN should perform three tasks, namely: a collection of structural data, local interrogation of collected data and wireless communication of collected data, and analysis of results [128]. A general schematic of WSN used for NDT is shown in Fig. 2.17.

![Figure 2.17: Schematic diagram of a general wireless sensor network for NDT.](image-url)
WSN consists of a sensing interface which connects with sensors/transducers in a structure and converts analog output from these sensors to a digital form. The sampling rate, number of channels and resolution must be set according to the specific need and type of monitoring. In most cases, the data thus obtained must be stored for some period before preparing for communication. The analog to digital conversion and storage can be performed using microcontroller and memory devices like Read only memory (ROM) or external memory card. Then, to send data through a wireless medium to the monitoring station, a radio/wireless transceiver is needed. The most common radio frequency used for radio transmission in health monitoring applications is 900 MHz and 2.4 GHz [16]. The wireless communication channel must be highly reliable with sufficient range. For this purpose, spread spectrum wireless signals are used commonly. In a few cases, besides collecting data from the sensors, WSN also need to perform as an actuation interface. In active sensors like piezoelectric sensors, actuation interface consisting of digital to analog converter can provide a voltage output for the excitation. Thus, WSN can act both as sensing and actuation interface [129]. There are many challenges associated with using WSN, especially providing power to the sensor and wireless device. Evident from the fact that, the main advantage of using WSN is to make sensing possible in complex and large structures, where it is difficult to reach and get the sensor results and where it is difficult to use wires. In such situations, sensor and wireless devices are powered mainly by batteries [130, 131]. Thus, it is equally necessary to develop WSN with a low power requirement.

WSN was used to monitor the bridge response to truck loading [126, 131]. [129] used WSN to monitor aircraft wing for defect detection and location estimation. WSN was used by [132] for monitoring blade deflection in wind turbine blades. Similarly, [133] used WSN to detect load position and loose bolt position in a composite plate. Similarly, WSN was used to detect damage in bolted joints [134].

2.6 Summary
From the literature review, it is clear that a large number of NDT techniques exist and each technique has its own advantages and application areas. The summary of the reviewed techniques is presented in Table 2.2 which presents the list of defects each technique are able to detect on different materials. NDT of each member of a structure
is not possible with a single technique. For this purpose, it is of utmost importance to utilise and combine different NDT techniques for overall monitoring.

**Table 2.2**: A matrix of application of different NDT techniques on different materials.

<table>
<thead>
<tr>
<th></th>
<th>Metal</th>
<th>Concrete</th>
<th>Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>millimetre</strong></td>
<td></td>
<td>b. Shallow surface flaws</td>
<td>b. Delamination</td>
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<tr>
<td><strong>wave sensing</strong></td>
<td></td>
<td>c. Corrosion</td>
<td>c. Hidden rust</td>
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<td></td>
<td></td>
<td></td>
<td>d. Thickness variation</td>
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<td></td>
<td></td>
<td></td>
<td>e. Voids</td>
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<td></td>
<td></td>
<td></td>
<td>f. Inclusions</td>
</tr>
<tr>
<td><strong>2. Laser</strong></td>
<td>a. Surface cracks</td>
<td>a. Cracks</td>
<td>None</td>
</tr>
<tr>
<td><strong>displacement</strong></td>
<td>b. Turbine blade</td>
<td>b. Vertical displacement</td>
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<tr>
<td><strong>sensing</strong></td>
<td>deflection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. Rail track profiling</td>
<td></td>
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<tr>
<td></td>
<td>d. Shape changes</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>e. Stiffness</td>
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<td></td>
<td>f. Through-gaps</td>
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<tr>
<td><strong>sensing</strong></td>
<td>b. Inclusions</td>
<td>b. Corrosion</td>
<td>b. Voids</td>
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<tr>
<td></td>
<td>c. Welding defects</td>
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<td>c. Heat damage</td>
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<td></td>
<td>d. Corrosion</td>
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<td>d. Cracks</td>
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<td>e. Debond</td>
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<td><strong>emission</strong></td>
<td>b. Joint defects</td>
<td>b. Creep</td>
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<td>c. Stress fatigue</td>
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<td><strong>imaging</strong></td>
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<td>b. Moisture content</td>
<td>b. Voids</td>
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<td>c. Hidden defects</td>
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<td>d. Moisture content</td>
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### 6. Fibre optics sensing

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<td>b. Weld defects</td>
<td>b. Shrinkage</td>
<td>b. Debond</td>
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<td>c. Creep</td>
<td>c. Deformation</td>
<td>c. Delamination</td>
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<td>d. Creep</td>
<td>e. Corrosion</td>
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### 7. Eddy current

<table>
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<th>a. Corrosion</th>
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<td>b. Fatigue cracks</td>
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<td>c. Hidden defects</td>
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<tr>
<th>a. Fibre orientation</th>
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<td>b. Gaps</td>
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### 8. Other optical sensing

<table>
<thead>
<tr>
<th>a. Hidden cracks</th>
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<td>b. Impact damages</td>
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<td>c. Vibration</td>
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<td>d. Turbine defects</td>
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<td>e. Strain</td>
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| a. Vibration |

<table>
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<tr>
<th>a. Cracks</th>
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<tr>
<td>b. Debond</td>
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<td>c. Delamination</td>
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The technique like microwave imaging has an advantage over other techniques, especially when we consider NDT of non-conducting materials as the microwave can easily penetrate inside these materials. On the other hand, the ultrasonic technique has an advantage for the NDT of a variety of conducting materials. The advantages of these different techniques can be utilised in conjunction for the NDT of a variety of construction materials. Conversely, the limitation of one technique can be overcome by using another technique. Moreover, different techniques can be integrated to overcome the limitation or improve the applicability and sensitivity of the technique. For instance, the optimisation of standoff distance is one of the microwave imaging problems. The distance measurement property of LDS can help to optimise standoff distance in complex-shaped structures. By developing integrated system software to combine both techniques, the advantage of each technique can be utilised.

As with all NDT techniques, besides the measurement, monitoring and control system, the network that connects them is vital. It is evident from the literature that using wired circuits for different sensors is impractical, especially when we consider scenarios that include large structures. Using WSN is one of the best ways of solving this problem. Thus, wireless systems with integrated sensing technique can be a versatile solution to NDT of a variety of construction materials and structures.
Chapter 3 Laser Displacement Profiling and Imaging for Surface Flaw Detection in Infrastructure Materials

3.1 Introduction

This chapter presents a novel laser displacement sensing system developed for surface profiling and imaging of a variety of infrastructure materials for surface flaw detection irrespective of their material property. The displacement measuring a property of laser displacement sensors (LDS) is utilised by scanning the sensor over the test specimen and generating one-dimensional and two-dimensional profiles of the specimen. The advantage of the proposed technique is that it is fully non-contact and the profiling and surface flaw detection can be performed in variety of infrastructure materials with different dielectric, chemical and physical properties. The background on the different surface flaw detection technique is provided with a focus on laser displacement techniques. A detailed description of the measurement principle of LDS is given, and the uncertainty analysis for the measurement is performed. The LDS technique has been applied for two specific applications: one-dimensional profiling and flaw detection in infrastructure materials, and two- and three-dimensional imaging and flaw detection of civil infrastructures. The measurement approach with comprehensive description of the system development procedures for both these applications is provided. The developed system was tested on a variety of specimens composed of different materials. The specimens ranged from metal, polymer, dielectric material to cement based specimens. The profiles and images were generated and then analysed for detection of flaws such as cracks, cuts and holes. Further, quantification of these damages was performed using statistical indexes such as root mean square deviation.

3.2 Background

Civil infrastructures include buildings, bridges, roads, tunnels, power plants, wind turbines, dams and heritage structures [21]. Early detection of damage and subsequent repair and retrofitting will help to prevent failures of these infrastructures as their failure can lead to significant public safety and economic effects. These early
preventive measures ensure that these infrastructures operate safely and efficiently over their intended lifespan and also save expenditures on maintenance and replacement [135]. These infrastructures are geometrically complex with various elements and joints and composed of different materials including concrete, metal, wood and composite materials [2].

Among these different materials, concrete is abundantly used in civil infrastructures because of its durability. However, several factors such as externally applied and environmental loads, error in design and poor construction practices may lead to its deterioration effecting flaws such as cracks and blowholes [136]. These flaws not only affect the appearance of the structure but also leads to a loss of durability [137] and their assessment is crucial for safety as well as for cost-effective maintenance [138, 139]. Cracks initially occur on the surface of the critical parts of concrete structures due to variable load and ageing and propagate inside the materials causing further degradation. Similarly, in other infrastructure materials such as metals polymers and timbers, fatigue and subsequent failure usually originates from the surface as a crack and propagates inwards. The detection of these relatively small cracks in these materials is an essential and challenging task, in particular for the concrete structures with a complex shape such as joints and columns. Flaws might be present in the surface of both plain (such as plain walls, rectangular columns or slabs) and non-plain (such as cylindrical beams, joints and columns) structures. These structures can have different geometric shapes and sizes, and detecting flaws at an early stage is still a challenge. Presence of the structural features often masks an indication of minute flaws, especially when using optical detection or imaging techniques. In these techniques, complex signal processing is required such as relaxation and adaptive thresholding probabilistic method to extract an indication of flaws and remove unwanted indications. Therefore, there is a need to develop a simple and practical system that can detect minute surface flaws in plain and non-plain structures irrespective of the infrastructure material being used.

Several studies related to the detection of surface flaws in civil infrastructures using different imaging techniques have been reported. Microwave and millimetre wave imaging techniques have been used to detect fatigue cracks in metal [34, 140] and
in recent years, few research studies have been performed in the field of crack detection in cement-based materials. Near-field microwave method was used to detect surface-breaking cracks in mortar and hardened cement-paste samples using open-ended-rectangular waveguide [141]. Although the technique is applicable for flaw detection in different materials, the imaging system is complex and may require different antennas and operating frequency or frequency band for different materials. Also, coaxial cable sensor was used along with time-domain reflectometry (TDR) for crack detection in a concrete structure, but this method was not able to detect initiation of crack from surface and the sensors needed to be embedded inside the concrete [142]. Similarly, an impedance-based method was used for crack detection in concrete structures which needed the piezoelectric-based sensors to be bound to the structure under test [138]. Different parameters of Rayleigh wave sensed by an accelerometer which was attached to the surface of the reinforced concrete block under impact were analysed to detect an artificial crack on the surface of the reinforced concrete [143]. However, this method needed direct surface contact of sensor and also needed external impact which is not always practical. Laser technique has also been used for flaw detection in civil infrastructures. Laser Doppler Vibrometer (LDV) was used to detect artificial surface flaws in concrete [144]. However, this method needed external impact from shock tubes. LDV was also used to monitor deflection and vibration of bridge and the results were compared with contact sensors [145]. Nevertheless, this technique needed reflective tape to be attached to the bridge during monitoring which is not practical. Also, this technique was not able to detect minute flaws such as cracks.

Terrestrial laser scanning methods have been used to detect larger flaws on bigger surface areas using multiple laser sources and high speed cameras [146, 147]. These methods need complex signal processing and are mainly applicable in large areas but are not suitable to detect minute surface flaws. Laefer et al. [148] tried to address this problem by presenting fundamental mathematics to determine minimum crack width in unit based masonry using terrestrial laser scanners. The absolute errors of crack widths were still 1.37 mm which is useful for investigating large areas but is not useful to detect minute crack widths. From this, it is clear that terrestrial laser scanning methods are mainly applicable in large scale survey and monitoring and they require
bulky instrumentation system and complex data processing [149]. However, laser
displacement sensor (LDS) system is based on different principle and mainly focuses
on local inspection for detection of smaller flaws. LDS techniques have been applied
to monitor defects in wind turbine blades by regularly monitoring the displacement
between the blade and tower during the operation [46, 150, 151]. Further, displacement
measurements have been used in several applications, in particular for measurement
of surface roughness and/or profile of a structure. For instance, LDS was used to
determine the smoothness of wood and to measure different profiles for different wood
species [52]. However, LDS techniques have not been used to detect minute surface
flaws in variety of infrastructure materials.

3.3 Measurement with Laser displacement sensor (LDS)

Laser displacement sensor (LDS) is a displacement detecting tool that gives the output
based on the distance of an object from the sensor head. It uses a laser beam to measure
distance in non-contact mode. The LDS consists of the laser head, detector, power
supply and RS422 to USB connector to connect the sensor directly to the computer.
The picture of LDS used in this study is optoNCDT 1302 from MicroEpsilon as shown
in Fig. 3.1.

![Figure 3.1: Laser displacement sensor (LDS).](image)

LDS head employs triangulation measurement principles with a laser emitter
projecting an infrared laser beam that creates a spot on the surface of a test specimen.
The light reflected from the surface is detected by the light receiver inside the sensor
head. The schematic of LDS employing triangulation measurement principle is given in Fig. 3.2. No special surface preparation is needed for the reflected light since the light receiver detects some of the light scattered from the surface. If the light spot changes its position, this change is imaged on the receiving element and evaluated. LDS uses a semiconductor laser with a wavelength of 670nm (visible/red). The sensor is classified as laser class II [152].

![Schematic of LDS](image)

**Figure 3.2:** Triangulation principle to measure distance using LDS.

Few terms need to be defined to describe the property and functionality of LDS.

a. Sampling/Measuring rate: Sampling rate is a rate of obtaining data samples from the sensor or can also be defined as a frequency of updating range output by LDS. The sampling rate of LDS is adjustable depending upon the need of measurement. The maximum sampling rate of LDS is 750 Hz.

b. Accuracy: The accuracy of LDS can be defined as a difference that can be expected between the sensor’s reading and an actual displacement value. Accuracy can be affected by the target specimen’s reflectance, the presence of other ambient lights or temperature change. In most cases, the accuracy can be defined in terms of resolution for LDS. Resolution is the smallest change in a distance that sensor can detect.
The sensor is capable of giving precise measurement result with a dynamic resolution of 100 µm at 750 Hz sampling.

c. Range resolution: The smallest change in a distance that sensor can detect along the line of sight of the laser can be defined as range resolution. In this case, the range resolution is the same as dynamic resolution which is 100 µm.

d. Spatial resolution: Spatial resolution can be defined as the smallest change in a distance that sensor can detect along the scanning plane. The spatial resolution depends on two factors namely, the sampling rate of LDS and scanning step of the platform or scanner in which the LDS is placed.

e. Linearity: Linearity is defined as the largest deviation from a best-fit straight line over the measurement range. The linearity of LDS is 400 µm which is ± 0.2% of Full-Scale Output.

f. Laser Power: The optical power level emitted by the laser in the sensor is defined as laser power. The maximum optical output laser power is 1mW.

g. Range: The minimum and maximum distance to which the sensor can measure distance accurately is defined as a range. The measurement range of LDS is from 20 mm to 200 mm where 20 mm is the start of the measurement range (SMR), and 200 mm is the end of the measurement range (EMR).

h. Spot diameter: Spot diameter is defined as the diameter of the spot made by the emitted laser on the surface of the target. The spot diameter varies according to the distance of the sensor from the target. The spot diameter at the SMR is 2300 µm while it gets down to 2100 µm at EMR.

An unsigned digital value is assigned to each digital output from RS422 into a control centre which is connected to LDS. The digital values are listed in Table 3.1.
Table 3.1: Digital values for each measurement range [153].

<table>
<thead>
<tr>
<th>Digital value</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 39</td>
<td>SMR back-up</td>
</tr>
<tr>
<td>40 - 4055</td>
<td>Measurement range</td>
</tr>
<tr>
<td>4056 - 4095</td>
<td>EMR back-up</td>
</tr>
<tr>
<td>16370 - 16383</td>
<td>Error codes</td>
</tr>
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</table>

From this digital value, a measurement value is obtained in mm using the following formula:

\[
x[\text{mm}] = \left( \text{digital}_{\text{OUT}} \times \frac{1.02}{4096} - 0.51 \right) \times MR[\text{mm}]
\]

(3.1)

where \( MR [\text{mm}] \) = Measuring range in mm.

3.3.1 Source of uncertainties during the measurement from LDS

The following are the factors that might cause uncertainty during the measurement of the displacement data using the LDS:

a. Light from other sources: The integrated optical interference filters present in the LDS suppresses maximum light from other sources. However, this does not preclude the possibility of interference from other light sources if the objects being measured are shiny and if lower measurement frequencies are selected.

b. Colour differences: The colour difference of targets affect the measuring result to a small degree because of the intensity compensation. These type of colour differences are often combined with different penetration depths of the laser light into the materials which results in apparent changes of the measuring spot size leading to errors.

c. Temperature influences: A warm-up time of at least 20 minutes is required before using the sensor to achieve uniform temperature distribution throughout the sensor. The damping effect of the heat capacity of the sensor results in a delay in the measurement of sudden temperature changes which might cause errors. The effect of temperature fluctuations should be considered while taking measurements in micron accuracy range.
d. Mechanical vibrations: The measurement in micron accuracy range is susceptible to mechanical vibration effect, and thus, special care must be taken to ensure stable and vibration free mounting of sensors and targets.

e. Movement blurs: If the measurement rate is set to low for fast moving objects, movement blurs may arise. Due to this reason, a high measurement rate should be chosen for high-speed operations to avoid errors.

f. Surface roughness: A surface roughness of 5 µm or more could lead to apparent distance change which is also called as surface noise. This effect can be reduced by averaging the measurements.

g. Angle influences: Tilt angles of the target around X- and Y- axes of less than 5° only affect the measurement of the highly reflecting surface. Tilt angles between 5° and 15° lead to an apparent distance change of approximately 0.12 – 0.2% of the measuring range. The tilt angles between 15° and 30° lead to an apparent distance change of approximately 0.5% of the measuring range. These effects must be considered when scanning the surface with high tilt or angle.

These errors have been taken into account during the measurement and precautions have been taken to reduce the influence of these uncertainties. Proper shields were used to remove the effect of other light sources during the measurement. The sensor was warmed up more than half an hour before the measurements, and the vibrations of scanners and other mechanical parts were kept to a minimum. The optimal measurement rate was chosen for all the measurements, and the influence of angle was considered.

3.4 One-dimensional profiling and flaw detection in infrastructure materials

LDS has been used to generate a surface profile of different specimens, and our study was focused on generating a 1-D profile of different materials. During the process of this measurement, we noticed that minute cracks give a sharp change of reading in the displacement scale. Using LDS as a displacement detecting tool is essential mainly
because of its non-contact remote nature and high sensitivity. Detecting minute cracks using displacement measurement have not been reported yet. Thus, this method was further investigated, and a measurement approach for surface flaw detection using 1-D profiling was developed [154].

3.4.1 Measurement approach

LDS measurement system consists of LDS mounted on a scanner to perform a raster scan over the specimen and a control centre. An LDS from Micro-epsilon includes a laser head and a detector and works on the triangulation principle by generating displacement reading at every laser spot onto the surface of the specimen under investigation. The displacement reading was received onto the controller PC where it was plotted in real time using the developed LabVIEW program with GUI interface by synchronising the sampling rate of the LDS with the step size of the scanner. The exposure time of measurement is different for dark and shiny objects and thus exposure time required for a concrete surface is longer than for a metal surface. According to this criterion, the sampling rate of LDS was set to 200 samples/s so that there is enough exposure time for all surfaces.

To generate a 1-D profile, LDS was placed above the specimen at a certain distance within its range. The scanner was then moved on a 1-D plane as shown in Fig. 3.3. The step size of the scanner was chosen to be 0.1-mm. The smaller the step size, the more accurate are the results. The step size of the scanner was also the spatial resolution of the LDS as it was synchronised with the measurement rate. This synchronisation resulted in LDS measuring at each step of the scanner. When LDS moved along the scan path over the specimen, real-time displacement reading could be observed in the LabVIEW platform in a controller PC. In the presence of a crack, there was a corresponding change in displacement reading which was indicated by a sudden peak in the displacement curve. In the LabVIEW program, the parameters such as sampling rate, resolution, communication port and width of the scanning area needed to be given by the user. The displacement curve was seen in real time which was a 1-D profile and which indicated presence/absence of crack. Further, the location of the crack along a scan path could also be determined. The displacement data was then saved for further analysis.
To quantify the crack, Root Mean Square Deviation (RMSD) was used as an index of crack or a crack indicator. For this purpose, RMSD was given by

\[
RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{N} (z(i) - z_0(i))^2}{\sum_{i=1}^{N} (z(i))^2}} \times 100 \quad (3.2)
\]

where \(z(i)\) and \(z_0(i)\) are displacement reading with crack and no crack, respectively at every measuring point.

### 3.4.2 Specimens

The specimens used in this study can be divided into two categories: metal and dielectric materials, and cement based materials. First, for the proof-of-concept of the 1-D profiling system, an aluminium profile with complex curvatures was used as shown in Fig. 3.4a. This specimen was specifically used as it was a strong and highly reflecting target and was easier for LDS to generate a 1-D profile. Next, a 1-mm cut was made in the specimen, and the system was used to detect the cut. The top view of the metal specimen with through-cut is given in Fig. 3.4b and the side view is given in Fig. 3.4c. To prove the applicability of the system in dielectric materials, a specimen made up of compressed polyvinyl chloride (PVC) with a 2-mm crack was selected which is shown in Fig. 3.5.
Figure 3.4: Metal specimens: (a) metal profile and metal profile with 1-mm through cut: (b) top view and (c) side view.

Figure 3.5: Dielectric specimen with 2-mm crack showing three scan paths.

Then, crack detection in two cement-based specimens were carried out. One specimen was a concrete slab with dimensions of 70 mm x 70 mm x 24 mm. This specimen was a cut-out portion of a bigger slab and was polished to eliminate the influence of surface roughness. It can be seen from Fig. 3.6 that the surface of the specimen consisted of
coarse aggregates and mortar with different values of brightness. Also, the surface had visible minute pores in the mortar. The specimen had the through the crack with 0.7-mm width on the top surface.

![Figure 3.6: Concrete slab specimen with 0.7-mm surface width crack: (a) top and (b) side view.](image)

Another specimen was a cylindrical concrete with a diameter of ~104 mm. The surface of this specimen contained only mortar without any indication of coarse aggregates. This specimen was loaded in compression using a testing machine until multiple cracks

![Figure 3.7: Cylindrical concrete specimen with multiple cracks: (a) perspective view, (b) close up view of the investigation area with variable width crack (c) schematic of the top view with two values of the incident angle, α.](image)
with different width occurred due to the loading effect as shown in Figs. 3.7a-b. The investigation area of this specimen included both the change in profile and the cracks. Fig. 3.7c shows changes of the incident angle, $\alpha$, when the sensor moves over a scan plane.

### 3.4.3 Profiling and flaw detection in metal and dielectric materials

Fig. 3.8 shows the displacement reading (D) vs position of laser spot along a 120-mm scan path for metal profile shown in Fig. 3.4a. The step size was chosen to be 0.1 mm. Most of the actual profile of the metal matched with this 1-D scan profile. As expected bigger profile change such as a big bulge in the centre of the scan path was seen in the 1-D profile and the dimension of this bulge was also accurate. The width of the bulge from the profile was determined to be $\approx 18$ mm which is similar to the real bulge as shown in Fig. 3.4 a. Similarly, the distance between the base of the bulge and the arc was determined to be $\approx 21$ mm. However, smaller profile changes with curves such as the corner angular bulges did not correspond to the 1-D profile. The main reason for this difference is the sharp angle of these angular bulges. Further, there were several shadow zones around the corner where the reflected light from corners did not reach the LDS because of the shape of the profile. However, this result shows that the 1-D profiling technique can be used to profile metal structures.

![Figure 3.8](image)

**Figure 3.8:** Displacement reading (D) vs position of laser spot along the scan path for metal profile.
Although the actual profiles matched with the generated 1-D profile in the previous result, our primary target was flaw detection in metal. For this reason, metal profile with through-cut was scanned along the scan path of 20-mm and step size of 0.1 mm, and the corresponding 1-D profile was plotted in Fig. 3.9. It is clear from the figure that the through-cut was clearly visible. Further, the dimension of the through-cut could also be estimated from this 1-D profile. From the profile, the depth (D) was determined to be ~ 43 mm which matches the depth of the real specimen if the thickness of the top plate (~ 1 mm) is considered. However, we can see in Fig. 3.9 that the dimension of the through-cut was not accurate in the profile (~ 2 mm). This inaccuracy is mainly due to the larger spot diameter of the laser beam. The spot diameter of 2.1 mm means that although the flaws could be detected, the accurate quantification of flaws below this diameter cannot be accurately quantified. For accurate quantification of flaws below this diameter, laser with smaller spot diameter is needed.

![Figure 3.9: Displacement reading (D) vs position of laser spot along the scan path for metal profile with through-cut.](image)

### 3.4.4 Investigation of the effect of the direction of scan path on flaw detection

A dielectric specimen composed of compressed PVC with 2-mm crack was used to investigate the effect of the direction of scan path on flaw detection. In real-life structure, the direction of crack/ flaw is unknown, and there is a need to develop a system which can detect flaws propagating in any direction. For this reason, a point of
interest along a crack was selected and then three scan paths of distance 20 mm were chosen at the different direction of crack. Scan path 2 was perpendicular to the crack while scan path 1 and scan path 2 were at some angle with crack. The change in the direction of the scan path changed the position of the laser spot hitting the boundary of the crack which in turn resulted in the different measured distance. The main purpose of this study is to inquire if this change would mask the flaw.

Fig. 3.10a shows the 1-D profile along the scan path 1 with a step size of 0.1 mm. There was a clear indication of a crack along this scan path. The uneven profile is mainly because of the surface roughness of the specimen. The sudden rise and fall of the displacement curve are due to the laser spot from LDS hitting the edge of the boundary and base of the boundary at a corresponding step.

Similarly, Fig. 3.10b and 3.10c show the 1-D profile along the scan path 2 and 3 with a step size of 0.1 mm. There was a clear indication of cracks along both these scan paths as well. However, the characteristic of a crack along scan path 1 and 3 are different from the crack along scan path 2. Scan path 1 and 3 being at an angle to the direction of crack showed a sharp rise and fall along the 1-D profile. However, scan path 2 being perpendicular to the crack did not hit the boundary of the crack and showed a single sharp change in profile at the position of crack.

The results above show that flaw detection using the LDS system is not dependent on the direction of flaw. The characteristic of the flaw might change, but that does not affect the indication. Further, the characteristic of the indications could be improved by reducing the step size.
Figure 3.10: Displacement reading (D) versus position of laser spot along the scan path for dielectric specimen along (a) scan path 1, (b) scan path 2 and (c) scan path 3.
3.4.5 Flaw detection in cement-based specimens

Next, flaw detection along planar and cylindrical cement-based specimen was performed. Fig. 3.11a shows 1-D scan profile as the mean curve with confidence intervals for displacement reading vs position of laser spot along 20-mm scan path on the surface of a concrete slab specimen. The 0.7-mm width surface crack was in the middle of the scan path. The result was obtained from the scan path which started at 25 mm along X-axis and 67 mm along Y-axis, i.e. at point (25, 67) (c.f. Fig 3.6a). The maximum standard deviation for five trials was 0.07 mm which shows significant repeatability rate. The indication of crack is distinctly visible in this curve. The surface roughness can also be visualised in the curve; however, the indication of crack is prominent. Fig. 3.11b demonstrates a resultant curve showing displacement reading change (ΔD) obtained by subtracting crack and no crack condition data. Here and further in this paper, to obtain a curve with no crack, the characteristic response of crack was removed, and polynomial extrapolation was done on the displacement curve.

![Figure 3.11: Concrete slab with 0.7-mm width crack: (a) displacement reading (D) vs position of laser spot along the scan path and (b) indication of the crack.](image)

Figs. 3.12a-b (left) shows the results of 1-D scan across a long crack on the surface of a cylindrical concrete specimen with 2-mm and 0.6-mm width, respectively. The results were obtained from two scan paths which started at points (15, 32) and (15, 40), respectively, (c.f. Fig. 3.7b). The indications of cracks are distinctly visible in both cases with bigger displacement reading change (ΔD) for 2-mm width crack than for 0.6-mm width crack as shown in Figs. 3.12a-b (right). The maximum standard deviations obtained were 0.05 mm and 0.04 mm, respectively.
To quantify the indication of crack, Root Mean Square Deviation (RMSD) was used as an index of crack. Fig. 3.13 shows that the RMSD = 0.59 and 0.2 for 2-mm and 0.6-mm width crack, respectively. The RMSD values gave a good indication of the presence of crack and the values correlated with the extent of crack width.

**Figure 3.12:** Concrete cylindrical specimen with (a) 2-mm and (b) 0.6-mm width crack: (left) displacement reading (D) vs position of laser spot along the scan path and (right) indication of the crack.

To further investigate the influence of curvature (i.e., the incident angle) on the crack detection, the scan path was set to be 100 mm to cover the entire diameter of the cylindrical specimen. The incident angle is defined as the angle between a laser beam incident on the surface of the specimen and a tangent that touches a cylindrical curve of the specimen at the incident point. The position of the same crack was changed from location A to location B by rotating the specimen to change the incident angle, as

**Figure 3.13:** RMSD for 2-mm and 0.6-mm width cracks in concrete slab.
shown in Fig. 3.14b. Fig. 3.14c shows the mean curvature of 1-D profile scan and the location of crack at two incident angles (left and right). Figs. 3.14d shows the resultant curve at locations A and B, respectively, which show similar characteristic responses. These resultant curves were obtained by subtracting crack and no crack condition data. The results showed that it is possible to get the reading of displacement and its change indicating crack at a wide range of $\alpha$ from $\sim0^\circ$ - $\sim180^\circ$. This result highlights the fact that the proposed method provides accurate and effective crack detection at different incident angles.

**Figure 3.14:** Cylindrical concrete specimen with cracks: (a) A schematic of the top view of semi-cylindrical part of the specimen with two locations A and B of a 2-mm width crack, (b) the displacement reading $(D)$ vs position of laser spot along the scan path around (left) crack location A, (right) crack location B and (c) corresponding indication of the crack.
3.5 Two- and three-dimensional imaging and flaw detection of civil infrastructures

In the previous section, the LDS technique was used to detect minute cracks in plain and cylindrical concrete surface by generating their one-dimensional (1-D) characteristic displacement responses. In this section, a simple non-contact imaging system with LDS for surface flaw detection of civil infrastructure materials has been developed [155, 156]. The developed system is able to provide a 1-D profile of structure surface as well as its two-dimensional (2-D) images. However, this section is focused on 2-D images of plain and non-plain metal and concrete specimens. The application of the developed system for 2-D imaging and profiling of dielectric and metal specimens and the detection of surface cracks in the plain concrete based specimen is given. For this purpose, novel software and algorithms have been developed and incorporated in the multifunctional computerised scanning mechanism with relatively smooth and fast motion. The performance of the proposed system was tested and verified by its application for imaging of metal and concrete specimens. Firstly, the imaging through the cut of the metal profile is performed to demonstrate the ability of the system to test its interior structure with different surface roughness and tilt. Secondly, 2-D images of the surface of plain and cylindrical concrete specimens are generated and analysed for the detection of minute cracks.

3.5.1 Measurement approach and materials

The measurement system mainly consists of LDS mounted on the scanning platform and control and data acquisition unit as shown in Fig. 3.15. The receiver inside LDS images the diffuse element of the reflection of the light spot and averages the measured values to give accurate output displacement value. The LDS has a micron accuracy range and is able to detect a minute change in displacement reading at different ambient temperatures. However, as discussed previously, warm-up time of 20 min is required to achieve uniform temperature distribution in the sensor for micron range measurement at fluctuating temperature.
Figure 3.15: Schematic of LDS imaging system.

The scanning platform and LDS were connected to the control and data acquisition unit as shown in Fig. 3.15. This unit controlled the movement of the scanning platform and acquired data from the LDS for further processing. The scanning platform performed a raster scan over the specimen. The LabVIEW based software program was developed for the control and data acquisition unit to receive the displacement reading from the LDS. Fig. 3.16 shows the block diagram of the system including four modules. A hardware control module was used to give commands to the scanner and LDS for initialisation, motion and measurement providing scan area and step sizes to the scanner, and the sampling rate to the LDS. A synchronisation and data acquisition module sent a trigger signal to LDS for data acquisition after each movement of the scanner, and LDS acquired displacement data. In a data processing and visualisation module, series of data at each alternate axis were flipped to compensate for the raster scan. The new set of data was then mapped based on the coordinate of the scan area. The real-time preview of the 2-D image could be seen in LabVIEW graphic user interface. The data was then saved for further processing in MATLAB R2014a.

A post-processing module provided generation of images and their processing using smoothing by giving proper colour representation and the image enhancement by performing the interpolation. Each colour in the 2-D image represented the distance of the LDS from each scan point at the surface of the specimen. The smoothness of the 2-D image was further improved by performing spatial averaging which is an image processing technique. In this technique, averaging was done on the data of n x n adjacent points, repeated an arbitrary number (k) of times. This type of spatial
averaging is known as iterative spatial averaging \((n \times n_k)\). The optimal value chosen for spatial averaging was \(3 \times 3\). Here, the peak-to-peak value of each data set was determined by taking the \(3 \times 3\) sliding window spatial mean filters along the highest and lowest displacement area [157]. This averaging removed unwanted noise in the signal and gave an accurate measure of highest and lowest distance. Thus, 2-D and 3-D images were generated where the reading was represented by colour and both by colour and displacement, respectively.

**Figure 3.16**: Block diagram of LDS imaging system.

### 3.5.2 Specimens

Different specimens with different material properties were used for imaging. The first group of specimens were washers to provide the proof of concept of the developed imaging system. The first specimen was a circular metal washer as shown in Fig. 3.17a. The circular metal washer had an outer diameter of 32 mm and the inner diameter of 13 mm with a thickness of 2.1 mm. The second specimen used for imaging was a circular plastic washer as shown in Fig. 3.17b. The circular plastic washer had an outer
diameter of 30 mm and the inner diameter of 7 mm with a thickness of 3.2 mm near the centre. The size of the scan area for both washers was 40 mm x 20 mm. Only half of the washers were taken as a scan area for imaging in order to demonstrate the details of the side view.

![Circular washer](image)

**Figure 3.17**: Circular washer: (a) metal and (b) plastic.

For the investigation of flaws, two groups of specimens were used. One group was based on a metal profile with a through cut, and another group included concrete-based specimens with surface flaws. Concrete blocks were used for the detection of the flaws such as cracks and blowholes on the plain surface. A cylindrical concrete specimen was also used to demonstrate the feasibility of the proposed system for the detection of surface flaws on the non-plain surface of the concrete. The description of these specimens is given in the respective section with the imaging results.

### 3.5.3 Profiling using 2-D imaging approach

Fig. 3.18 shows the 2-D image of half of the circular metal washer. As we can see from Fig. 3.18a, the circular ring in the washer is clearly visible in the front view. The thickness of the washer was determined to be ~2.2 mm from the colour bar as shown in the side view in Fig. 3.18b which is similar to the real thickness of the metal washer.

Fig. 3.19 shows the 2-D image of half of the circular plastic washer. The circular ring of the washer was clearly visible in the 2-D image as shown in Fig. 3.19a. Similar to the previous case, the thickness was determined to be ~3.1 mm from the colour bar as shown in the side view in Fig. 3.19b. The thickness determined from the colour bar...
showed good matching with the original thickness of the washer at the measured position.

Figure 3.18: 2-D plot of a circular metal washer: (a) front view and (b) side view.

Figure 3.19: 2-D plot of a circular plastic washer: (a) front view and (b) side view.

The above two results prove that applicability of the system for accurate detection of surface profiles. The study also provided a background study for the 2-D and 3-D imaging system to apply for flaw detection in a variety of materials.
3.5.4 Imaging of metal profile with through cut

Figs. 3.20a-b show the top view and side view of the metal profile with a through cut in the 2-mm thick top plate, respectively. A 2-mm thick bottom plate of the metal profile was movable. The cut had a width of 1-mm (cf. Fig. 3.20a) and the distance between the top and the bottom plates of the profile was 42 mm (cf. Fig. 3.20b). The size of the scanned area was 5 mm x 5 mm (cf. Fig. 3.20a), and the step size was set to be 0.5 mm. Figs. 3.20c-d show the 2-D image and side view of the 3-D image of the scanned area, respectively. The indication of the cut is seen in the 2-D image, and a few observations can be made from Figs. 3.20c-d. The width of the cut in the image is wider than its actual width due to the relatively large size of the laser beam which is bigger than the width of the cut. The colour bar and displacement reading show that the laser radiation (i.e., part of its beam) penetrates through the cut and the radiation reflected from the bottom plate is picked up by LDS. It can be seen from Fig. 3d that the displacement reading shows the distance between two plates of the profile which is equal to the actual distance between these plates (i.e., 42 mm).

**Figure 3.20:** Picture of the metal profile with through cut and its images: (a) top view and (b) side view of the profile; (c) 2-D image and (d) side view of 3-D image.
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The results show that the proposed technique is able to detect flaws in the surface of the profile and to sense its inner structure through the cut. To confirm this and to investigate the feasibility of this technique with a through cut for other applications this specimen was further used to investigate the effect of changes of distances between the plates as well as changes of tilt angle and surface roughness of the bottom plate. The metal surface of the bottom plate was exposed or covered with a paper sheet to investigate the influence of surface roughness/smoothness on the reading.

Firstly, the distance between the top and bottom plates d1 was changed by moving the bottom plate parallel to the original position as shown in Fig. 3.21a and, secondly, tilt angle was changed by changing the distance between through cut and the bottom plate (referred to as d2) as shown in Fig. 3.21b. These two configurations were used with both the exposed and covered bottom plate.

![Image](image_url)

**Figure 3.21:** Picture of the profile with the bottom plate covered by a paper sheet and moved to be: (a) parallel and (b) tilted to its initial position.

Figs. 3.22a-b show the 2-D and side view of 3-D images of the profile through the cut with an exposed bottom plate at distances d1 of 32 mm and 21.5 mm, respectively. Similarly, Figs. 3.22c-d show the 2-D and side view of 3-D images of the cut with a covered bottom plate at distances d1 of 32 mm and 21.5 mm, respectively. Both sets of the images show a clear indication of the cut and the inner profile through the cut. The images at d1 of 32 mm are identical (cf. Figs. 3.22a-c) while there is a slight difference between images of the exposed and covered bottom plate at d1 of 21.5 mm which can be attributed to scattering of light from the paper sheet. These results show
that the smoothness/roughness of the profile can affect indication of the bottom plates at small distances between the cut and the bottom plate.

**Figure 3.22:** 2-D images (left) and side view of 3-D images (right) of the profile obtained through the cut for the exposed and covered bottom plate at two distances d1: (a) exposed and 32 mm, (b) exposed and 21.5 mm, (c) covered by the paper sheet and 32 mm and (d) covered by the paper sheet and 21.5 mm.

Figs. 3.23a-b show the 2-D and side view images of 3-D images of the profile through the cut with an exposed tilted bottom plate at distances d2 of 32 mm and 21.5 mm, respectively whereas Figs. 3.23c-d show the similar images with the covered bottom plate. As expected, the images with both the exposed and covered plate at 32 mm are identical (cf. Figs. 3.23a-c). However, when the distance d2 was decreased to 21.5 mm
in the exposed surface, LDS could not obtain displacement reading at some points from the bottom plate. Due to the increase in tilt angle, the light reflected off the smooth exposed bottom plate did not reach the LDS but were scattered. This resulted in the loss of displacement reading which can be seen in the images. However, for the same increase in tilt, the light reflected off the rougher surface of paper reached LDS.

Figure 3.23: 2-D images (left) and side view of 3-D images (right) of the profile through the cut for the exposed and covered bottom plate at two distances $d_2$: (a) exposed and 32 mm, (b) exposed and 21.5 mm, (c) covered by the paper sheet and 32 mm and (d) covered by the paper sheet and 21.5 mm.
The results of this investigation show that further decreasing the d2 (increasing tilt angle) decreases the quality of images. For example, at d2 of 18 mm, there is no displacement reading from the bottom plate in the exposed surface. The range of the colour scale of the image was reduced to visualise the small change in displacement which indicated the lower value of the change in displacement reading mainly because of the reflection of the fraction of the laser radiation from the edges of the cut as shown in Fig. 3.24a. However, there was still a good indication of the cut as well as the inner profile for the covered bottom plate as shown in Fig. 3.24b. The results of this investigation show that the main contribution in the indication of cut came from the reflection off the edges of the cut.

**Figure 3.24**: 2-D images (left) and side view of 3-D images (right) of the profile through the cut, and the (a) exposed and (b) covered bottom plate at d2 = 18 mm.

The real distances between the top and bottom plate were compared with the distances obtained from the side view of 3-D images. The comparison was performed for both exposed and covered bottom plate using a statistical tool called cross-correlation technique. The cross-correlation technique applied to the newly fetched data and the reference data gives a coefficient value known as correlation coefficient providing information about the similarity of the data with the reference data. The coefficient
value ranging from 0 to 1 quantify the linear correlation between two data sets, and the lower coefficient value can be an indicator of a deviation of measured distance from the real distance. The correlation coefficient \((r)\) is given by the equation [158]:

\[
r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{(n(\sum x^2) - (\sum x)^2)} - \sqrt{(n(\sum y^2) - (\sum y)^2)}}
\]  

(3.3)

where, \(n\) is the number of data points, \(x\) is the reference distance, and \(y\) is the measured distance.

The results show that the correlation coefficient between the real distances and obtained distances for the exposed bottom plate was 0.9999 while for the covered bottom plate, it was determined to be 0.9995 for a non-tilted bottom plate. These values indicate that the obtained distances in both exposed and covered cases match the real distances. For the tilted bottom plate, the correlation coefficient between the real distances and obtained distances for the exposed bottom plate was 0.9987 and for the covered bottom plate was 0.9993. Although both coefficients are high which indicates that the measured distance matches the real distances, the measured distances with covered bottom plate were more accurate compared to the exposed bottom plate.

### 3.5.5 Surface flaw detection in cement-based specimens

The 2-D images were generated for the detection of minute flaws such as cracks and blowholes in the cement-based specimens. Firstly, a mortar block with cracks was tested with a measurement system as shown in Fig. 3.25.

![Figure 3.25: Picture of measurement system testing a mortar block.](image)
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The mortar block had a dimension of 235 mm x 100 mm x 100 mm and a 1-mm width through the crack as shown in Fig. 3.26a. Two locations along the crack designated as A and B with different directions of crack were imaged at the scan area of 5 mm x 5 mm and the step size of 0.5 mm. Figs. 3.26b-c show the 2-D images of the scanned area at location A and B, respectively. The 2-D images and side views of 3-D images indicate the presence of the crack at different orientations. Contrary to the metal profile, the majority of the laser beam hitting the base of the crack was reflected which was indicated by the higher value of the change in displacement (~ 4 mm in crack A and ~ 1.2 mm in crack B). These values correspond to the actual crack depths.

![Figure 3.26](image)

**Figure 3.26:** Mortar block: (a) picture showing scanned area at locations A and B along 1-mm width crack, 2-D (left) and side view of 3-D images (right) where cracks are represented by colours and displacement values at location (b) A and (c) B.

Next, a concrete block with three flaws on the surface was investigated. The concrete block had a dimension of 350 mm by 100 mm by 100 mm as shown in Fig. 3.27a. The size of the scanned area around each flaw was chosen to be 10 mm x 10 mm. The first flaw was a 1-mm width natural crack. Fig. 3.27b upper shows the 2-D image of the scanned area over the crack. The crack was clearly visible in the 2-D image. The
second flaw was a ~3-mm diameter blowhole (referred to as hole 1). The depth of this blowhole was ~3 mm. Third flaw was a ~1.5 mm diameter blowhole (referred to as hole 2). The depth of hole 2 was ~2 mm. The upper rows of Figs. 3.27c-d show the 2-D image where an indication of both blowholes can be distinctly observed. The side view of the 3-D image of the scan path indicated the presence of flaws represented by colours and displacement value as shown in lower rows of Figs. 3.27b-d. These images showed a clear indication of crack and blowholes. Further, as we can see from Figs. 3.27c-d (lower), the depth of blowholes can be estimated. Similar to the previous case, the value of the change in displacement is higher in crack due to the reflection of the laser beam from the base of the crack. In the case of the blowhole, the reflection of the laser beam was from the combination of edges and the base of the hole.

![Concrete specimen: (a) picture showing scanned areas over crack and blowholes, 2-D (upper) and side view of 3-D images (lower) where flaws are represented by colors and displacement values for (b) crack, (c) hole 1 and (d) hole 2.](image)

**Figure 3.27:** Concrete specimen: (a) picture showing scanned areas over crack and blowholes, 2-D (upper) and side view of 3-D images (lower) where flaws are represented by colors and displacement values for (b) crack, (c) hole 1 and (d) hole 2.
Finally, to check the applicability of the proposed system for flaw detection in the non-plain surface, a cylindrical concrete specimen with a diameter of ~104 mm was used which contained several natural cracks as shown in Fig. 3.28a. These cracks of different widths and lengths occurred when the specimen was loaded in compression using a testing machine. The scan area (30 mm x 5 mm) included both the cylindrical profile and a 1-mm crack. It was expected that these flaws could be masked by the profile change. However, the 2-D image of the scan area clearly indicates the crack running through the middle of the scan area and the change in the profile of the specimen was also visible as shown in Fig. 3.28b. The side view of the 3-D image of the scan area also showed both the profile and clear indication of a crack. The characteristic curve of crack is similar to the curve for the crack obtained in previous cases.

![Figure 3.28](image)

**Figure 3.28:** Cylindrical concrete specimen: (a) picture showing scanned area, (b) 2-D (upper) and side view of the 3-D image (lower) where profile and crack are represented by colours and displacement values.

The results demonstrated the feasibility of the proposed imaging system for the detection of surface flaws such as cracks and holes in a variety of construction
materials. The effect of tilt and surface roughness on the detection of surface cut and sensing capability of the inner structure of metal through the cut was investigated. The results showed that flaw detection could be achieved on both smooth and rough surface but at a high tilt angle, the rougher surface is needed for accurate profiling of inner surface through the cut. The main contribution of the indication of flaw came from the reflection off the edges of the flaw. The significant fraction of the laser beam is reflected in case of rougher surface like concrete leading to more accurate depth approximation compared to a smooth surface like metal. In cement-based specimen, the generated images showed the surface flaws such as cracks and blowholes in both plain and non-plain specimens. The developed system is capable of generating surface profiles at high speed with a capability of scanning an area of 50 mm x 50 mm within a minute and a real-time defect detection feature. Relatively narrow cracks with a width of 1-mm were clearly observed; moreover, the developed system work as a foundation for the detection of even smaller width cracks, blowholes and impact damages on the surface of infrastructure materials using higher resolution LDS.

3.6 Summary

In this chapter, a novel LDS profiling and imaging system was developed for surface flaw detection in a variety of infrastructure materials. The developed system could robustly detect different defects with correct locations and defect size estimation. The imaging system was used in two different applications: 1-D profiling and 2-D and 3-D imaging.

First, 1-D profiles of different specimens were generated. The results showed that the measurement technique and method with LDS could be used for crack detection and evaluation in a concrete specimen which was indicated by the sharp displacement reading the change in the 1-D profile scan path. The crack was visible at an exact position which is indicated by the characteristic response of crack and its location. Further, the confidence interval obtained from the standard deviation was very low which proved the repeatability and feasibility of this technique.

Next, LDS imaging system was developed and applied for 2-D imaging of metal and concrete specimens. It was shown that the system could provide the inspection of the
interior structure of the metal profile using 2-D imaging through a cut in its plate. In this case, surface roughness and tilt of the interior structure components play a critical role and may compensate the influence of each other. For example, the increase of tilt of the surface may destroy its images through the cut, but the increase of the surface roughness may recover the images at some ranges of the tilt and roughness level. The applicability of the system for non-contact inspection of plain and cylindrical concrete specimens for detection of surface flaws such as cracks and blowholes has also been demonstrated. The developed system can be used for profiling and non-contact inspection of structures made of construction materials such as metal, plastic and concrete.

The developed system and technique can overcome critical problems in detecting cracks in concrete as well as in other conducting and non-conducting materials. The 2-D imaging of cylindrical concrete specimen for the purpose of detection of surface flaws such as cracks using a single LDS has not been reported yet. It is shown that this technique is a robust and economical solution to the surface flaw detection in plain and non-plain specimens. The imaging through the cut of the metal profile has been done for the first time to demonstrate the ability of the developed system to test its interior structure and to test the limitation of the imaging at different surface roughness and tilt. The system is non-contact, relatively simple and robust and can be placed and moved practically anywhere, even in remote locations. The system was able to detect defects with width as small as 0.6 mm with the capability of detecting smaller cracks with higher resolution LDS and better scanning system. The LDS system could further be used with different NDT systems such as microwave imaging systems to provide effective inspection of the surface as well as the interior structure of engineered materials which is given in Chapter 5.
Chapter 4 Microwave Imaging for Defect Detection in Planar Construction Materials and Structures

4.1 Introduction

This chapter presents the development of a microwave imaging system for defect detection in planar and tilted construction materials and structures. Even though there are numerous NDT techniques, non-invasive methods for NDT of diverse construction materials and structures are relatively at an early stage of development. As discussed in the previous chapter, laser displacement imaging system was used to detect surface flaws in a variety of construction materials. Here, the microwave imaging system has been used to detect hidden and surface flaws in a variety of materials including metals, dielectric materials, composite materials and cement based specimens. In this chapter, background on microwave non-destructive testing technique has been provided with a focus on near-field microwave measurement technique. A detailed description of 3-axis multifunctional microwave imaging system and all its components including signal generation and data acquisition module, scanning module and control and visualisation module has been illustrated. The uncertainty analysis for the measurement using PNA has been performed. Next, the developed imaging system has been applied in detection and visualisation of flaws in a variety of materials. These materials have been broadly divided into two categories: metal-based composite material and cement based composite material. Further, proof of concept for the development of wireless microwave imaging system has been provided. A simple spot measurement technique has been used to show the applicability of the wireless microwave sensing system which is a proof-of-concept for the wireless microwave imaging system. The main objective of this chapter is to demonstrate the methodology and different application of microwave imaging system and better understand the advantages and limitations of the microwave technique.

4.2 Microwave non-destructive testing technique

The microwave frequency spectrum spans from about 300 MHz to 30 GHz with the corresponding wavelength ranging from 1,000 mm – 10 mm, while millimetre wave
frequency spectrum ranges from 30 GHz to 300 GHz with the corresponding wavelength ranging from 10 mm – 1 mm. The frequency and wavelengths associated with microwave and millimetre waves are shown in Fig. 4.1. The signals at these frequencies can readily penetrate inside the dielectric material and interact with their inner structure which is an advantage of microwave technique over other conventional techniques for interrogation of a variety of materials. Further, the microwave technique does not require a coupling medium and is non-contact in nature in contrast to other NDT techniques such as an ultrasonic technique which requires a couplant for contact between sensors and specimen [159].

**Figure 4.1**: Microwave and millimetre wave frequency ranges and associated wavelengths.

Microwave imaging techniques have been applied to a wide variety of commercial and scientific applications such as non-invasive testing and evaluation, material characterisation and medical application [43, 160-162]. Near-field microwave non-invasive techniques, utilising open-ended rectangular waveguide probes/antennas, have demonstrated the ability to detect flaws in various dielectric and composite materials using relatively simple microwave reflectometers. These materials include construction materials and composites such as metal, concrete, cement-based materials and CFRP-strengthened concrete structures possessing flaws such as delaminations, debonds and cracks [34, 38, 163]. Typically, microwave imaging is performed by scanning a single antenna over an object at some distance between the antenna and the specimen under test which is referred to as the standoff distance. Microwave images are produced using reflected signal data obtained over a two-dimensional scanned area and, if necessary, signal and image processing [141].
4.2.1 Near-field measurement techniques
Microwave near field measurement techniques utilise probes such as open-ended rectangular waveguides, open-ended coaxial lines, monopole antennas, resonators based on different applications [43]. Besides probe, one of the key components of near-field measurement technique is microwave frequency generator and detector. The detector converts amplitude modulated microwave signals to baseband signals, and an inbuilt comparator gives an indication when a threshold power is reached. The parameters of interest for near-field measurements are mainly phase and magnitude of the reflection coefficient, phase and magnitude of transmission coefficient, reflected and transmitted power, standing wave properties and so on. These parameters are also based on specific applications, and one or multiple parameters can be used to extract necessary information for inspection and damage visualisation. Relying on these parameters, there are two distinct measurement techniques: calibrated and uncalibrated techniques. Calibrated techniques are used when the defect needs to quantified while the uncalibrated techniques are used mostly in applications for defect detection and visualisation which only needs relative information. The calibrated measurement technique measures parameter referenced to a specific measurement plane within a system such as the aperture of the microwave probes and thus provides quantifiable information about the parameters. However, our measurement is mainly concerned with damage detection and have used uncalibrated microwave measurement techniques.

4.2.2 Uncalibrated microwave measurement techniques
This type of measurement does not require calibration as the goal of this technique is defect detection where the quantifiable information about the parameters is not required. The relative information about the presence of defect and properties is sufficient for this technique. There is a wide variety of uncalibrated microwave measurement technique that depends on the measured parameter of interest. For instance, debond in thick sandwich composites are detected using the phase of reflection coefficient while rust under paint in the low-loss dielectric composite are detected using the magnitude of the reflection coefficient. However, the results might not be entirely dependent upon the phase or magnitude of a signal due to the unwanted signal leakage and reflections from the microwave circuits.
Fig. 4.2 shows a general schematic of near-field, non-contact and one-sided measurement system which is used throughout this chapter. An oscillator feeds a microwave sensor/probe via a directional signal divider. This is done so that a portion of the transmitted signal is available to be compared to or mixed with the reflected signal. The major portion of the signal supplied by the oscillator is transmitted out of the sensor and incident onto the specimen under inspection. The incident signal interacts with the specimen, and a portion of it is reflected back to the sensor. The reflected signal is then transmitted to the signal analyser via a directional signal divider. An Agilent N5225A performance network analyser (PNA) is used as a signal analyser in this study for this purpose. A detailed description of the measurement using PNA is given in the next section. The magnitude and/or phase of these two signals are compared, and a signal proportional to their difference is fed into an indicator. Figs. 4.3 and 4.4 illustrate general designs for a phase and a magnitude detector, respectively.
The microwave probe/sensor is moved over the specimen under inspection using different scanning mechanisms such as raster scan and C-scan. The traditional C-scan and raster scan techniques are similar where the sensors are moved along X- and Y-axis scan pattern over the test specimen. However, in the phased array C-scanning technique, the sensor is typically moved physically along one axis while the beam electronically scans along the other axis. The reflected signal from the specimen
changes if any defects or flaws are present. The change in the phase and/or magnitude of the reflected signal due to any of the defects once compared with the reference signal in the signal analyser indicates the presence of the defect. This change may also be used to obtain information about the spatial extant, the type of defect encountered and its size.

4.3 Imaging system and measurement approach
The 3-axis multifunctional microwave imaging system consisted of three different modules: signal generation and data acquisition module, scanning module and control and visualisation module.

![Diagram of microwave imaging system](image)

**Figure 4.5:** Microwave imaging system testing a specimen with flaws: (a) schematic and (b) image of a laboratory prototype.
The signal generation and data acquisition module consisted of Agilent N5225A performance network analyser (PNA). The schematic of the imaging system testing a specimen with flaws is shown in Fig. 4.5a while the actual image of the laboratory prototype is shown in Fig. 4.5b.

4.3.1 Measurement with Performance Network Analyser (PNA)

A Performance network analyser (PNA) N5225A from Agilent was used. This PNA can generate 10 MHz to 50 GHz microwave signals having two ports with a single source. The PNA as shown in Fig. 4.6 has high output power (up to +13 dBm) and a wide power sweep range (up to 38 dB) with a best dynamic accuracy of 0.1 dB compression with +12 dBm input power at the test port. Under this measurement setup, Agilent N5225A PNA can be used to generate microwave signals at R-band (1.7 GHz – 2.6 GHz) and X-band (8.2 GHz – 12.4 GHz). For this study, X-band microwave signals have been used because the short wavelength of this band allows for higher resolution imaging for target identification and hence, damage detection. The operation of PNA can be divided into five major functional groups [164]:

a. Synthesised source group: This part generates swept, stepped or continuous wave signal in the desired frequency ranges. The source group provides five signals, one local oscillator signal and four incident signals.

b. Signal separation group: Each of the incident signals from the source group is separated into a reference path and test path. The reference signal is transmitted to the receiver group while the test signal is transmitted through and reflected from the antenna and is then transmitted to the receiver group.

c. Receiver group: The receiver converts the test and the reference signal to 7.438 MHz intermediate frequency (IF) signals for signal processing and retains both magnitude and phase characteristics. The IF signals are then converted to digital information by the digital processing group.

b. Digital processor and digital control group: The digital processor group is further divided into front panel group and data acquisition and processing group. The front panel group provides communication to the
network analyser while the data acquisition and processing group performs signal processing and analyser control and then provides the output to the display.

e. Power supply group: This group provides power to the other assemblies in the instrument.

Microwave probes such as open-ended rectangular waveguides of R-band and X-band can be used as microwave sensors. The resolution of these sensor depends on the selection of probes. Finer cross-range resolution is achieved through wider beamwidth and scanning area, and finer range resolution is achieved through wider bandwidth [165]. Measurement data is received and stored in PNA for further processing. An object-oriented LabVIEW program controls the PNA via a GPIB interface.

![Agilent N5225A Performance Network Analyser (PNA)](image)

**Figure 4.6:** Agilent N5225A Performance Network Analyser (PNA).

Some of the parameters measured using PNA are as follows [166]:

h. Reflection coefficient ($\Gamma$): The reflection coefficient is the ratio of the reflected signal voltage level to the incident signal voltage level.

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} \quad (4.1)$$

The reflection coefficient can also be expressed in terms of impedance as:

$$\Gamma = \rho \angle \varphi = \frac{Z_L-Z_0}{Z_L+Z_0} \quad (4.2)$$
where $\rho$ is the magnitude of the reflection coefficient and $\varphi$ is the phase of the reflection coefficient, $Z_L = \text{Load impedance}$ and $Z_0 = \text{Source impedance}$.

The range of possible values for $\rho$ is between zero and one and is unitless. A transmission line terminated in its characteristic impedance will have all energy transferred to the load; zero energy will be reflected and $\rho = 0$. When a transmission line terminated in a short or open circuit, all energy is reflected and $\rho = 1$. For short circuit, the voltage of the reflected wave will be 180 degrees out of phase with the incident wave. For the open circuit, the voltage of the reflected wave will be in phase with the voltage of the incident wave.

i. Return loss: Return loss is a way to express the reflection coefficient in logarithmic terms (decibels). Return loss is the number of decibels that the reflected signal is below the incident signal. Return loss is always expressed as a positive number and varies between infinity for a load at the characteristic impedance and 0 dB for an open or short circuit. It is given by:

$$\text{Return loss} = -20 \log(\rho) \quad (4.3)$$

where $\rho = |\Gamma|$

j. Voltage standing wave ratio (VSWR): It is defined as the maximum value of the RF envelope over the minimum value of the RF envelope and is given by:

$$VSWR = \frac{E_{\text{max}}}{E_{\text{min}}} \quad (4.4)$$

k. Transmission coefficient ($T$): The transmission coefficient is defined as the transmitted voltage divided by the incident voltage. If the absolute value of the transmitted voltage is greater than the absolute value of the incident voltage, a device under test or system is said to have a gain. If the absolute value of the transmitted voltage is less than the absolute
value of the incident voltage, the device under test or system is said to have attenuation or insertion loss. It is given by:

\[ T = \frac{V_{\text{transmitted}}}{V_{\text{incident}}} \]  

(4.5)

1. **Gain**: The gain in dB is given by:

\[ \text{Gain (dB)} = 20 \log \left| \frac{V_{\text{transmitted}}}{V_{\text{incident}}} \right| \]  

(4.6)

### 4.3.2 Source of uncertainties during the measurement from PNA

There are mainly three types of measurement errors that can arise in measurement by PNA [167]. They are systematic errors, random errors and drift errors.

a. **Systematic errors**: Systematic errors are caused by imperfections in the test equipment and test setup. If these errors do not vary over time, they can be characterised through calibration and mathematically removed during the measurement process. Systematic errors encountered in network measurements are related to signal leakage, signal reflections, and frequency response. There are six types of systematic errors:

   i. Directivity and crosstalk errors relating to signal leakage
   
   ii. Source and load impedance mismatches relating to reflections
   
   iii. Frequency response errors caused by reflection and transmission tracking within the test receivers

b. **Random errors**: Random errors vary randomly as a function of time. Since they are not predictable, they cannot be removed by calibration. The main contributors to random errors are instrument noise, switch repeatability, and connector repeatability. When using network analysers, noise errors can often be reduced by increasing source power, narrowing the intermediate (IF) bandwidth, or by using trace averaging over multiple sweeps.

c. **Drift errors**: Drift errors occur when a test system’s performance changes after a calibration have been performed. They are primarily caused by temperature variation and can be removed by additional calibration. The rate of drift determines how frequently additional calibrations are needed. However, by
constructing a test environment with stable ambient temperature, drift errors can usually be minimised.

These errors have been taken into account during the measurement. Several procedures have been followed to keep the errors at a minimum. For example, use of proper connectors and waveguides, use of optimal power, maintaining the constant temperature during the measurement and averaging over multiple sweeps were carried out.

### 4.3.3 Scanning module

The scanning module comprised of components from National Instruments which included scan control unit, motion interface, drives and motors as shown in Fig. 4.7. The scan control unit consisted of an embedded controller and motion control card inside a chassis. The embedded controller with a 2.5 GHz processor and 8 GB RAM has multitasking, a real-time operating system to give the command to the other scanning units and to get the position feedback. Further, it handled host communications, command processing, multi-axis interpolation, error handling, general-purpose digital I/O, and overall motion system integration functions. The motion control card is a stepper motor controller which supports up to four independent or coordinated axes of motion. It also supports arbitrary and complex motion trajectories.

![Figure 4.7: Block diagram of the scanning module.](image_url)
The motion interface was connected to the motion control card through a 68-pin very high-density cable interconnect (VHDCI) connector which carried input and output signal for all axes using the configuration function as follows [168]:

a. The 68-pin shielded cable was connected between the Motion input/output (I/O) connector on motion controller and the Motion I/O connector on Universal Motion Interface (UMI).

b. The P7000 direct connect cable was connected between the UMI and the P7000 series stepper drive based on the wire colour code given in Table 4.1.

c. The NI UMI slide switches were configured. The UMI switches should be set to match the polarity configuration for the P7000 series stepper drive, as shown in Tables 4.2.

d. The power was connected to the NI UMI. For this, a +5 V external power supply was connected to the two-position terminal block labelled required inputs. The positive lead of the +5 V power supply was connected to the +5 V terminal, and the negative lead to the digital ground (GND) terminal.

The main purpose of the interface was to connect drives and feedbacks to the motion control card. It also powered the three stepper drives which were used to control the
stepper motors for corresponding X-, Y- and Z- axes. The motors were configured using National Instruments SoftMotion module, and the motion control was achieved by integrating with the LabVIEW program.

### 4.3.4 Control and visualisation module

The control and visualisation module is connected to both PNA and scanning module, and the main purpose of the control and visualisation module is to control the movement of scanner and to obtain reflection coefficient data from the PNA to generate microwave images. For this, an object-oriented LabVIEW program was developed with a GUI as shown in Fig. 4.8.

![Screenshot of the GUI used for control of the microwave imaging system and visualisation of microwave images.](image)

**Figure 4.8:** Screenshot of the GUI used for control of the microwave imaging system and visualisation of microwave images.

This module controlled the movement of the scanner such that the scanner performed a raster scan along X-Y coordinates while the Z-axis could be set to three kinds of motion. Z-axis could be set to do step movement by giving the step size which is
similar to the movement of X- and Y-axis or could be set to move along X-plane or Y-plane. Linear encoders along each axis provided position feedback. The movement along X- and Y- plane was sufficient for planar specimen while the movement of Z-axis was used for the tilted specimen. The software developed in the LabVIEW platform allowed manual control of the position of the antenna and calculated the path to scan, based on the start position, end position, and step size for each axis.

Figure 4.9: Scanning mechanism of microwave imaging system: (a) top view of the raster scan over the specimen, (b) side view of the scan over a planar specimen and (c) side view of the scan over a tilted specimen.

A simple raster scan along X- and Y- the plane was carried out for the planar specimen as shown in Fig. 4.9a based on the input parameters in GUI. For example, for a scan area of 14 mm x 14 mm and step size 2 mm, scanner started from coordinate (0, 0) and moved 7 steps along X-axis till it reached (14, 0). Then, it moved 2 mm along Y-axis
to reach coordinate (14, 2) and moved back along negative X-axis until it reached (0, 2). The process repeated till it reached the end of scan area at (14, 14). For this scan area, the scanner moved a total of 49 steps as shown in Fig. 4.9a. For planar specimen, the scanner moved along scan plane 1 parallel to the plane of specimen surface at a constant standoff distance as shown in Fig. 4.9b. However, for the tilted specimen, when the scanner moved along scan plane 1, the standoff distance changed. Due to this reason, the tilt of the specimen was measured, and the manual setting was done in the GUI based on this tilt and scan area to control the movement of Z-axis. Once this setting was inputted to the GUI, the scanner moved along scan plane 2 as shown in Fig. 4.9c at a constant standoff distance parallel to the surface plane of the tilted specimen. After this, the PNA recorded the magnitude and phase of the reflection coefficient at each step along the scan area.

Once the magnitude and phase of reflection coefficient were obtained, they were divided into the separate matrix and then mapped based on the step size and coordinate of the scan area. The real-time preview of the raw magnitude image could be seen in GUI. Further, MATLAB was used for smoothing and interpolation of the magnitude images. These images were used to visualise any flaws in the specimen under test. In most cases, images generated using the magnitude of the reflection coefficient is sufficient for the visualisation of crack and has been used in this study. However, images generated using the phase of reflection coefficient has been utilised during the comparison of the effect of perpendicular and parallel polarisation on damage detection.

4.4 Detection of flaws in metals and metal-based composite materials

Metals such as iron, steel and aluminium are abundantly used in construction materials and structures [8]. Besides, metals and alloys are also used in various mechanical structures such as aircraft fuselage, railroad tracks and car wheels, turbine blades, generators, engines and various machinery [169]. These structures are subjected to varying loads during their lifetime which often leads to fatigue failure [170]. Metal fatigue and subsequent failure usually originates from the surface as a crack and propagates inwards. Hence, surface crack detection of metallic structures is of utmost importance. Fatigue crack monitoring of metals and alloys are useful for the safe
running of these mechanical structures preventing injuries and financial loss [171]. It is also critical to know the exact location of the crack for repair and reinforcement. Lamb wave technique is one of the conventional methods for detecting fatigue cracks in metals. A piezoelectric transducer array was bonded to the metal surface, and damage indices were used to detect a surface crack in metal [172]. Similarly, a single piezoelectric transducer was attached on the metal surface, and laser doppler vibrometer was used to sense the lamb wave generated by the attached transducer [116]. In both these techniques, piezoelectric transducers need to be bonded to the surface of the metal which affects the structural integrity and might not be applicable in real life civil and mechanical structures. In the previous section, laser displacement sensor was used for profiling and through-gap detection in metal by generating one-dimensional profiles as well as two- and three-dimensional images of the surface of the metal specimen using the displacement value from the sensor. These techniques are useful in detecting cracks in metal but are mainly focused on surface crack detection. However, several machinery parts are painted or lined with thin-layered elastomeric materials such as rubber. The rubber linings are mainly used to reduce energy dissipation and to improve the efficiency of the machine, to eliminate the lubrication system, to protect the mechanical components from dust and to reduce vibration and noise generation [173]. In these cases, optical and lamb wave based crack detection system is inapplicable as they are not able to detect hidden cracks under the layer. The advantage of the proposed microwave techniques over these techniques is mainly due to the ability of microwave signals to penetrate inside dielectric materials which is useful for detecting and evaluating sub-surface cracks or cracks hidden under dielectric coatings such as paints or rubbers.

4.4.1 Inspection of metal in composite materials

To illustrate the ability of the system to detect targets such as metal in composite materials under conditions of constant and varied standoff distances, we used a layered construction foam structure backed by a metal plate with four embedded metal disks (each has a diameter of 15 mm and thickness of 1 mm). The dimensions of the foam structure were 180 mm by 180 mm by 90 mm. Figs. 4.10a and 4.10b showed two views of the schematic of the foam specimen tilted with respect to the raster scan plane (referred to as scan plane 1) of the sensing unit.
Figure 4.10: Schematic of the (a) side and (b) top view of a construction foam specimen with embedded metal disks tested by the sensing unit with an open-ended waveguide antenna (OEWA) moving over scan plane 1, and images obtained at tilt angle, $\theta$, of (c) $0^\circ$ and (b) $6^\circ$.

At tilt angle $\theta = 0^\circ$ (non-tilted specimen), the standoff distance is constant, and it is equal to the standoff distance at an initial position (home position) of the sensing unit, $d_o$, while at $\theta > 0$ the standoff distance $d$ varies, as shown in Fig. 4.10a. In this investigation, we scanned the part of the specimen with one disk located at a depth of ~15 mm (Fig. 4.10b). Figs. 4.10c and 4.10d show 8.2-GHz raw images of the metal disk obtained at $\theta = 0^\circ$ (Fig. 4.10c) and $\theta = 6^\circ$ (Fig. 4.10d). We used an open-ended waveguide antenna (OEWA) moving over scan plane 1 with $d_o = 38$ mm, with the scanned area of 90 mm by 90 mm and steps of 3 mm by 3 mm. The grayscale levels correspond to different values of magnitude of reflection coefficients. An indication of the disk is distinctly visible in the non-tilted specimen, i.e., at $\theta = 0^\circ$ (Fig. 4.10c). However, when the specimen is tilted, the image shows a gradual intensity change from right to left, representing the standoff distance change over the scanned area due to the specimen tilt. This change masks the indication of a relatively strong target, i.e. the metal disk. Overall, imaging of the metal disk embedded in a tilted construction
foam specimen is a challenging task though the disk is a strong target, as shown in the case of the non-tilted specimen.

To further illustrate the capability of the imaging system for the inspection of construction materials and structures, the detection and evaluation of cables and metallic bars on walls covered by plasterboard sheets was performed as shown in Figs. 4.11a-b. Schematic of the specimen with a 12-mm diameter steel rod located on a concrete surface under a plasterboard sheet is shown in Figs. 4.11c-d. It can be seen that the specimen is a layered structure of air – plasterboard – air – concrete with a hidden steel rod. First, a preliminary detection of the bar was conducted by using imaging at an arbitrary standoff distance. Then, a few spot-by-spot measurements were performed using a linear scan along Z axis to determine optimal standoff distance which provided the largest difference between magnitudes of reflection coefficients measured at places with and without a rod. Finally, a microwave image was generated, and it demonstrated the location of the rod and its important features such as its tip as shown in Fig. 4.11e.

Figure 4.11: Picture of the wall with cables and pipes: (a) before and (b) after covering by plasterboard sheets, and schematic of the specimen with a 12-mm diameter steel rod under a plasterboard sheet: (c) the side and (d) top view, and (e) microwave image.
4.4.2 Detection of flaws in planar metal specimen covered with dielectric materials

A few specimens were used in this investigation to illustrate the applicability of the system for the detection and evaluation of defects in the planar metal specimen with/without dielectric material cover. The term ‘planar’ is used to describe a metal specimen without any tilt as discussed previously.

The first specimen was a metal slab with the dimension of 400 mm x 54 mm x 7 mm with multiple holes as shown in Fig. 4.12. The specimen was taken from a machine part. The scanned area was chosen to be 54 mm x 42 mm to cover three holes – a 15 mm diameter large hole and two 8 mm diameter small holes on either side of the large hole. The microwave antenna was scanned at a standoff distance of 10 mm along the scan plane as shown in Fig. 4.12a and the step size of 3 mm were used. An open-ended
microwave antenna (OEWA) with output flange dimension of 41.1 mm x 41.1 mm was used. First, the antenna was scanned over the bare metal without any dielectric cover. Then, three different dielectric covers were used – 7 mm thick foam, 10 mm thick plasterboard and 3 mm thick rubber.

![Microwave images](image)

**Figure 4.13:** Microwave images of the scanned area of a metal specimen with multiple holes (a) without cover and with (b) foam, (c) plasterboard and (d) rubber cover.

Fig. 4.13 shows the 10.3-GHz raw magnitude images of the scan area of the metal specimen with multiple holes using OEWA. The image of the bare metal without any cover (cf. Fig. 4.13a) and the image of metal with a rubber cover (cf. Fig. 4.13d) gave the distinct indication of both large and small holes. The clear image with rubber cover is obtained mainly due to the absorption of reflected microwaves by a rubber layer. The absorption of the microwave signal by the rubber layer is mainly due to its high
permittivity and dielectric loss property. The indication of small holes is masked due to the presence of a large hole in metal with plasterboard cover (cf. Fig. 4.13c) while there was a faint indication of all three holes in metal with foam cover (cf. Fig. 4.13b). The weak indication of holes with plasterboard cover is mainly due to the interaction of the microwave with its inner structure. The indication of holes could be improved using OEWA with smaller aperture dimension which improves the spatial resolution.

Figure 4.14: (a) Schematic of the perspective view of the microwave antenna testing the metal specimen with 2-mm through the gap and (b) picture of the top view of the actual specimen.

The second specimen was made up of two metal slabs with a dimension of 150 mm x 150 mm x 20 mm and 2-mm through the gap between them. The scanned area was chosen to be 45 mm x 90 mm. The microwave antenna was scanned at a standoff distance of 10 mm along the scan plane as shown in Fig. 4.14a and the step size of 3 mm were used. An open-ended microwave antenna (OEWA) with output flange dimension of 41.1 mm x 41.1 mm was used. First, the antenna was scanned over the
bare metal slabs without any dielectric cover. Then, similar to the previous measurement, three different dielectric covers such as – 7 mm thick foam, 10 mm thick plasterboard and 3 mm thick rubber were used.

**Figure 4.15:** Microwave images of the scanned area of a metal specimen with 2-mm through the gap (a) without cover and with (b) foam, (c) plasterboard and (d) rubber cover.

Fig. 4.15 shows the 10.3-GHz raw magnitude images of the scan area of the metal specimen with 2-mm through-gap. Similar to the previous results, the image of metal with rubber cover gave a distinct indication of through-crack (cf. Fig. 4.15d). However, the indication of through-crack in bare-metal was not distinct compared to the previous result (cf. Fig. 4.15a). It is mainly due to the scattering of the microwave signal after reflection from the bare metal. However, this effect was minimal in metal with foam covering resulting in a distinct indication of through-gap (cf. Fig. 4.15b).
Likewise, due to the interaction of the microwave with the inner structure of the plasterboard, these structures can also be seen along with the through-gap in metal with plasterboard cover (cf. Fig. 4.15c).

### 4.4.3 Detection of flaws in tilted metal specimens covered with a dielectric material

The metal slabs used in the previous section was used in this investigation to illustrate the applicability of the system for the detection and evaluation of defects in the tilted metal specimen with/without dielectric material cover. These specimens were tilted at a certain angle and then scanned along the tilt (cf. Fig. 4.16). As explained previously, the information about tilt angle and scan area should be known prior to the scanning so that the movement of Z-axis can be adjusted such that the microwave antenna followed the profile along the tilt. In this case, the scanner was set to perform raster scan along X- and Y-axis over the scan area and the movement of Z-axis was set along Y-plane to follow the contour of the specimen which resulted in fixed standoff distance. Fig. 4.16 shows the schematic of the microwave antenna testing the tilted metal specimens with flaws covered with dielectric materials.

![Figure 4.16: Schematic of microwave antenna testing the tilted metal specimen with flaws and dielectric covering.](image)

The first specimen, metal with multiple holes (cf. Fig. 4.12b) was tilted at 8°, and then images were generated by scanning along the scan area 54 mm x 42 mm with a step size of 3 mm with and without dielectric coverings. The standoff distance of 10 mm was used. Fig. 4.17 shows the 10.3-GHz raw magnitude images of the scan area of the metal specimen with multiple holes using OEWA. As observed in the planar specimen,
the image of the bare metal without any cover (cf. Fig. 4.17a) and the image of metal with a rubber cover (cf. Fig. 4.17d) gave the distinct indication of both large and small holes. Although the indication of holes is clear, the quality of the image is affected by the tilt. In plasterboard cover, the indication of small holes is masked due to the presence of a large hole, and also the inner structure of the plasterboard is visible (cf. Fig. 4.17c). There was a faint indication of all three holes in metal with foam cover (cf. Fig. 4.17b).

Figure 4.17: Microwave images of the scanned area of a tilted metal specimen with multiple holes (a) without cover and with (b) foam, (c) plasterboard and (d) rubber cover.

The second specimen, metal with 2-mm through-gap (cf. Fig. 4.14b) was tilted at 10°, and then images were generated by scanning along the scan area 45 mm x 90 mm with a step size of 3 mm with and without dielectric coverings. The standoff distance of 10
mm was used in this measurement as well. Fig. 4.18 shows the 10.3-GHz raw magnitude images of the scan area of the metal specimen with 2-mm through-gap using OEWA. There was a faint indication of through-gap in bare metal (cf. Fig. 4.18a) and metal with foam (cf. Fig. 4.18b) and rubber (cf. Fig. 4.18d) coverings. However, there was no prominent indication of through-gap in metal with plasterboard covering (cf. Fig. 4.18c). Overall, the images were not clear compared to the planar specimen. It can be attributed to the steep tilt angle and the irregular contour following due to the manual setting.

![Microwave images of the scanned area of a tilted metal specimen with 2-mm through the gap (a) without cover and with (b) foam, (c) plasterboard and (d) rubber cover.](image)

**Figure 4.18**: Microwave images of the scanned area of a tilted metal specimen with 2-mm through the gap (a) without cover and with (b) foam, (c) plasterboard and (d) rubber cover.
4.5 Detection of flaws in the cement-based specimen and dielectric materials

Concrete is abundantly used in civil infrastructures because of its durability. The assessment of cracks in concrete structures is crucial for their safety and cost-effective maintenance since they affect not only their appearance but also the load-carrying capacity and durability [138]. Several non-invasive testing techniques have been under investigation for the purpose of crack detection in concrete. These include acoustic testing, ultrasonic technique, optical methods and microwave techniques. However, compared to the non-invasive methods for metal structures, the non-invasive methods for concrete structures are relatively at an early stage of development [141]. Microwave techniques have a high potential for the inspection of construction materials including concrete since microwave signals can penetrate inside generally lossy dielectric materials and can interact with their inner structure. A few research studies have demonstrated promising results in the field of crack detection in cement-based materials. An ultrasonic method was used to detect a crack in mortar samples using wave modulation technique [174]. Plastic optical fibre sensors were used to detect initial cracks in concrete beams subjected to loading conditions [175]. However, as mentioned in the previous section, microwave technique is an effective NDT technique for the concrete and cement based material due to its ability to penetrate inside dielectric material.

4.5.1 Inspection of planar and tilted layered dielectric material

A layered dielectric specimen was first used in this investigation to illustrate the applicability of the system for the detection and evaluation of defects. The specimen was a six-layered foam structure with a dimension of 225 mm x 225 mm x 50 mm and four embedded rubber disks. These disks were embedded at different layers of the foam specimen. This specimen was used to test the applicability of the developed system in layered materials.

First, this layered dielectric specimen was kept in planar position and then scanned along scan plane 1 and scan plane 2 as shown in Fig. 4.19b. Two different scan areas were considered for the scan: first scan area was 90 mm x 90 mm which was chosen to visualize single embedded rubber and was referred to as scan area 1 while the second
scan area was 210 mm x 210 mm which was chosen to visualize all four embedded rubber disks and was referred to as scan area 2. Then, it was tilted at 8° along Y-axis and scanned without manual adjustment of the scanner keeping the same scan plane (referred to as scan plane 1) as shown in Fig. 4.19a. Then, the Z-axis was adjusted to scan along the tilt using the manual setting. The information about tilt angle and scan area was provided for the movement of Z-axis which can be adjusted in such a way that the microwave antenna followed the profile along the tilt.

**Figure 4.19:** Schematic of the microwave antenna testing the layered foam specimen with embedded rubber disks: (a) side view, (b) perspective view and (c) top view of the specimen (left) and cross-sectional side views of the specimen showing the location of the rubber disks (right) inside the specimen.

Fig. 4.19 shows three views of the schematic of the tilted foam specimen being scanned by the microwave antenna along two scan planes, scan plane 1 and scan plane 2. The
scan plane 1 referred to the movement of scanner along X- and Y-axis without the Z-axis movement. This led to a variable standoff distance $d$ between the sensing unit and the specimen. The scan plane 2 referred to the movement of scanner along all three axes using the feedback from two LDSs which led to the constant standoff distance, $d_0$, between the sensing unit and the specimen.

Fig. 4.20 shows the 10.3-GHz raw images of the scan area 1 and 2 of the planar layered foam specimen using the magnitude of the reflection coefficient. The step size was set to be 3-mm along both X- and Y-axis at $d_0 = 15$ mm. The indication of embedded rubber disk was prominent along scan area 1 as seen in Fig. 4.20a. This is highlighted by the smooth colour of the image and a clear demarcation between the area with and without the embedded rubber disk. Along scan area 2, there were indications of all four embedded rubber disks. The colour of the four different rubbers was different in Fig. 4.20b because of the different depths of rubber disks in the specimen. For example, the rubber discs with prominent indication were positioned between the first and second layers of the specimen while the rubber disks with less prominent indication were positioned between the fifth and sixth layers of the foam specimen.

![Figure 4.20: Microwave images of planar layered foam specimen along (a) scan area 1 and (b) scan area 2.](image)

Fig. 4.21 shows the 10.3-GHz raw magnitude images of scan area 1 and 2 of the layered foam specimen tilted at 8° at scan plane 1. Although there was an indication
of rubber disks, the images and the region around the disks were blurred. It is mainly due to the standoff distance change due to which coloured gradients were observed resulting in a blurred image mainly around the boundary of the rubber disks.

**Figure 4.21:** Microwave images of tilted layered foam specimen at scan plane 1 along (a) scan area 1 and (b) scan area 2.

**Figure 4.22:** Microwave images of tilted layered foam specimen at scan plane 2 along (a) scan area 1 and (b) scan area 2.

Fig. 4.22 shows the 10.3-GHz raw magnitude images of scan area 1 and 2 of the layered foam specimen tilted at 8° at scan plane 2. The scanner was manually adjusted to follow the contour of the foam surface. The gradient effect was reduced, and the indication of rubber disks became more prominent as the contrast between the area
with rubber and without rubber increased. These images matched the image obtained for the planar specimen. However, some gradients were present which blurred the image around the boundary of the rubber (cf. Fig. 4.22a). This phenomenon was also observed along scan area 2 (cf. Fig. 4.22b). The gradients were mainly present due to the error in the measurement of tilt angle accurately.

4.5.2 Detection of crack in planar and tilted cement based specimens

A mortar block with a dimension of 23.5 cm x 10 cm x 10 cm with an artificial notch and natural through crack was used for the proof of concept of the microwave imaging system for crack detection in the cement-based specimen as shown in Fig. 4.23. The block was located on a tilted wooden plate, and the scanned area for each flaw (i.e., notch and through crack) was 45 mm x 90 mm (c.f. Fig. 4.23a). The side view of the mortar block is shown in Fig. 4.23b and side view of the mortar block covered by a 10-mm thick plasterboard sheet is shown in Fig. 4.23c.

Figure 4.23: Mortar block with a notch and through-crack: (a) top and (b) side view of exposed block and (c) side view of the block covered by a 10-mm thick plasterboard sheet.

In this investigation, we focused in the indication of the crack on the surface of the mortar block with relatively strong reflection and scattering of electromagnetic waves
from its edges in contrast to the investigation of the foam specimen where the influence of edges of the specimen was negligible due to the low dielectric permittivity of foam. Therefore, lower standoff distance and higher operating frequency were used in this case. The raw magnitude and phase images of cracks in cement-based materials were generated for both parallel and perpendicular polarisation for this specimen. In parallel polarisation, the antenna was adjusted so that the electric field polarisation vector was parallel to the crack while in perpendicular polarisation, the antenna was such that the electric field polarisation vector was perpendicular to the crack along the scan area. Once the scan was complete, besides the amplitude, the phase of the reflection coefficient at each point was saved to a file for post-processing.

**Figure 4.24:** Schematic of a setup with a side view of (a) non-tilted (planar) and (b) tilted specimen, and (c) top view of the setup.

The experimental setup for the planar specimen did not include the Z-axis movement of the antenna. The schematic of an experimental setup for testing planar specimen at constant standoff distance, \( d_c \), is shown in Fig. 4.24a. The experimental setup for the
tilted specimen is shown in Figs. 4.24b-c. The schematic of the perspective view of the experimental setup is shown in Fig. 4.25. The tilted specimen was tested using two scan planes: scan plane with variable standoff distance, \( d \) and scan plane 2 with constant standoff distance, \( d_c \).

**Figure 4.25:** Schematic of a perspective view of the experimental setup.

The step size of the scanner in all the test was set to 3-mm along both X- and Y-axis. Similar to the planar case, the raw magnitude and phase images were generated from the obtained reflection coefficient data. First, images of scan area with the notch have been obtained at parallel and perpendicular polarisation with respect to the notch in a tilted specimen.

Figs. 4.26 and 4.27 show raw 11.5-GHz images of the scan area for mortar block with 2-mm width notch tilted at 3.8° using magnitude and phase of the reflection coefficient at parallel polarisation. The initial standoff distance \( d \) was set to 6 mm. The raw images of scan area with the notch at scan plane 1 (c.f. Figs. 4.26a and 4.27a) obtained at the variable \( d \) shows a gradual intensity change from left to right along X-axis, representing the standoff distance change over the scanned area due to the sample tilt. There is a very weak indication of the notch which is masked by the gradual intensity change. When scanning at scan plane 2 (i.e., at constant \( d_c \) as shown in Fig. 4.24b) the
gradual intensity changes reduced significantly, and there was an indication of the notch in the raw images as shown in Figs. 4.26b and 4.27b. However, the indication was blurry.

**Figure 4.26:** Raw images of the notch in the mortar specimen tilted at 3.8° using the magnitude of reflection coefficient (parallel polarisation) obtained at: (a) scan plane 1 and (b) scan plane 2.

**Figure 4.27:** Raw images of the notch in the mortar specimen tilted at 3.8° using phase of reflection coefficient (parallel polarisation) obtained at (a) scan plane 1 and (b) scan plane 2.
Figs. 4.28 and 4.29 show raw 11.5-GHz images of the scan area for mortar block with 2-mm width notch tilted at 3.8° using magnitude and phase of the reflection coefficient at perpendicular polarisation. The standoff distance \( d \) was kept similar to the previous case. Similar to the results in parallel polarisation, the raw images of scan area with the notch at scan plane 1 (c.f. Fig. 4.28a and 4.29a) showed very weak indication of the notch which is masked by the gradual intensity change. When scanning at scan plane 2 (i.e., at constant \( d_c \) as shown in Fig. 4.24b) the gradual intensity changes significantly reduced, and the indication of the notch became more prominent in the raw images as shown in Figs. 4.28b and 4.29b. It was observed that raw images using perpendicular polarisation gave a prominent indication of notch compared to the parallel polarisation and thus perpendicular polarisation is used hereafter.

\[
\begin{array}{c}
\text{(a)} \\
\text{(b)}
\end{array}
\]

**Figure 4.28:** Raw images of the notch in the mortar specimen tilted at 3.8° using the magnitude of reflection coefficient (perpendicular polarisation) obtained at: (a) scan plane 1 and (b) scan plane 2.
Figure 4.29: Raw images of the notch in the mortar specimen tilted at 3.8° using phase of reflection coefficient (perpendicular polarisation) obtained at (a) scan plane 1 and (b) scan plane 2.

Fig. 4.30 shows raw 11.5-GHz images of a 2-mm width notch in a non-tilted mortar block at perpendicular polarisation. These images were obtained at a standoff distance of 10 mm. It can be seen that there are indications of the notch in both raw magnitude and phase images (c.f. Figs. 4.30a-b) and these indications are very similar to those obtained in the case of tilted specimen shown in Figs. 4.28b and 4.29b. The small difference between images for non-tilted and tilted specimen can be attributed to different standoff distances (10 mm vs 6 mm).

Figure 4.30: Raw images of the notch in the non-tilted mortar specimen using: (a) magnitude and (b) phase of the reflection coefficient.
Similar measurements were taken along the scan area with the crack. In addition, to demonstrate the effectiveness of the proposed system for crack detection under dielectric coating, a 10-mm thick plasterboard sheet was placed on top of the mortar block between the antenna and the mortar specimen. Firstly, measurements were performed with an exposed tilted and non-tilted specimen at different standoff distances and frequencies. Secondly, the specimen was covered by a dielectric coating (10-mm thick plasterboard sheet) and investigated at different frequencies.

Fig. 4.31 shows magnitude images of the crack in an exposed mortar specimen tilted at 3.8° obtained at a frequency of 11.5 GHz at two standoff distances when the specimen was scanned at scan plane 2. An indication of the crack can be clearly seen at a relatively small standoff distance of 6 mm (c.f. Fig 4.31a) while blurring indication of the crack was obtained at a higher standoff distance of 26 mm as expected (c.f. Fig. 4.31b).

![Image of magnitude images](image)

**Figure 4.31:** Magnitude images of the crack in an exposed mortar specimen tilted at 3.8° (scan plane 2) obtained at a frequency of 11.5 GHz and at a standoff distance of (a) 6 mm and (b) 26 mm.

Images of the crack in a non-tilted and exposed specimen obtained at a standoff distance of 26 mm and at three frequencies are shown in Fig. 4.32. In this case, the indication of the crack is more prominent than in the tilted specimen at the same standoff distance of 26 mm and frequency of 11.5 GHz (c.f. Figs. 4.32a and 4.31b). It is also better than the indication of crack at a lower frequency of 8.52 GHz (c.f. Fig.
4.32b), and its quality is comparable with the quality of the indication of crack at a higher frequency of 12.3 GHz (c.f. Fig. 4.32c).

**Figure 4.32:** Magnitude images of the crack in an exposed and non-tilted mortar specimen at a standoff distance of 26 mm and at a frequency of (a) 11.5 GHz, (b) 8.52 GHz and (c) 12.3 GHz.

Finally, Fig. 4.33 shows images of the crack in a non-tilted specimen covered by 10-mm thick plasterboard sheet at three frequencies. The standoff distance was set to be 4 mm for this test (i.e., the distance between the antenna and the surface of the specimen, in this case, was 14 mm). The 11.5-GHz image demonstrates the indication of crack which is comparable with the non-covered case, but the background of the
image is more non-uniform due to the influence of the coating (c.f. Figs. 4.33a and 4.32a). Non-uniformity of the background increases at a lower frequency (c.f. Fig. 4.33b) and higher frequency (c.f. Fig. 4.33c).

Overall, the obtained images showed a good indication of the notch and the crack. The 3-axis multifunctional scanning system makes it possible to scan microwave antenna over tilted structures in addition to the plane surface and to manually optimise standoff distance. The gradual intensity changes in both magnitude and phase images were observed at variable $d$ which masked the indication of the surface flaws. On the other hand, when scanned at constant standoff distance the indication of flaws was prominent. The images at perpendicular polarisation showed better clarity than the images at parallel polarisation. The indication of the surface crack was obtained in both exposed and covered cases.

### 4.6 Development of wireless microwave sensing system

The previous sections showed the results using wired microwave imaging system which proves the applicability of the microwave imaging system in a wide variety of construction materials and structure. However, with bulky instrumentation system and wired configuration, it is difficult to utilise this technique in real-world application. For this reason, the aim was to provide a proof-of-concept for wireless microwave sensing system which is applicable in wireless microwave imaging system as well. Near-field microwave technique includes spot measurement as well as imaging techniques for material characterisation and damage detection of these materials. The spot measurement technique involves measurement of microwave properties as well as detection of defects such as gaps in different cement-based materials and layered specimens using a single microwave antenna [176, 177]. For the proof-of-concept of wireless microwave sensing system, a spot measurement technique was utilised. The spot measurement technique is a simple microwave non-destructive testing technique without a need for complex data processing and image processing. A portable wireless spot measurement technique has an advantage over conventional wired measurement technique which not only reduces the complexity of the system but also enables remote monitoring of the materials. For this reason, we have developed a wireless microwave sensing system for non-destructive testing of materials. The data acquisition part of
the microwave sensing system is replaced with a wireless data acquisition system. It consists of a sensor that is used to interrogate a target specimen. The output from the sensor is generally an analog voltage signal which is then converted to a digital signal using analog to digital converter. A microcontroller is mainly used for analog to digital conversion while a dedicated analog to digital converter can also be used. The converted digital signal is then transmitted to the RF (radio frequency) communication device which may operate at different frequencies. Some of the common RF communication devices that are being used are Zigbee, Wi-Fi module and RFID module [178-180]. Microwave technique has been used for wireless power transmission and wireless communications including radar, navigation and remote sensing applications [181]. However, the use of wireless data acquisition system for near-field microwave sensing technique is a novel concept. The different microwave antenna combinations were used on a foam specimen with embedded rubber disk to test the applicability of the system.

4.6.1 Wireless data acquisition system

The wireless data acquisition system consists of a LORD Microstrain V-Link LXRS wireless sensor node and a wireless USB base station. They operate on IEEE 802.15.4 physical radio specification at 2.4 GHz. V-Link wireless sensor node consists of four differential and three single-ended analog input channels. The measurement range for the single-ended input channel is from 0 – 3 V. The inputs have a 16-bit resolution, and full-scale measurement accuracy is ± 0.1%. The node supports continuous, period burst and even triggered sampling with a sampling rate up to 10 KHz for periodic burst sampling and 512 Hz for continuous sampling. It has a data storage capacity of 4 MB. The outdoor line of sight range is up to 2 km, and the indoor range is 50 m [182].

The internal architecture of a wireless sensor node is shown in Fig. 4.34. The output voltage of the sensor is fed on to the single-ended analog input channel of the wireless sensor node. Inside the node, the analog voltage is first converted into the digital signal and then stored temporarily on the flash memory before being transmitted through the 2.4 GHz transceiver antenna.
The wireless sensor nodes have three operational modes: active, sleep, and idle. When the node is sampling, it is in active mode. The node is put into an idle mode to stop the sampling. Idle mode is used for configuring node settings (such as frequency and sampling rates) and is the only way to stop sampling or go between active and sleep modes. Sleep mode is an ultra-low-power mode. The node will automatically go into sleep mode after a user-settable period of inactivity. The node will not go into sleep mode while sampling.

4.6.2 Wireless USB base station

Wireless USB base station is a wireless data acquisition gateway and provides communication between the wireless sensor node and the monitoring computer. The gateway transmits a continuous, system-wide timing reference known as the beacon for precision sampling synchronisation. It supports a data rate of up to 921,600 bps [183]. The base station’s transceiver antenna receives the transmitted data from the transceiver antenna of the wireless sensor node. The base station is connected to the monitoring computer through USB 2.0 serial communication. For communication, the base station should be connected to the USB port of the monitoring computer and then configured. The configuration is performed using Node Commander software.
Node Commander is used to configure sensors nodes, set sampling parameters, and begin data acquisition. In Node Commander, the wireless sensor node is linked with the base station using the node discovery feature. The node starts transmitting a message with its operating frequency to the base station once the node discovery feature is activated. The software then assigns a channel number to the node and the configuration and calibration is done using the window as shown in Fig. 4.35. In this window, parameters such as channel label, conversion coefficient, gain, input range and calibration values are given.

A GUI and data acquisition program are developed using LabVIEW platform for wireless data acquisition. After the configuration is completed, parameters such as communication port, node address and a number of sweeps are given in LabVIEW GUI. The real-time data from the sensor is obtained and plotted as a graph in GUI, and the data is simultaneously saved for further processing.
4.6.3 Measurement approach and specimen

The schematic of a wireless microwave sensing system is shown in Fig. 4.36. The system can mainly be divided into two units: sensing and transmitting unit, and receiving unit. Sensing and transmitting unit consists of an Agilent N5225A performance network analyser (PNA) as described earlier in section 4.3. The calibration of the setup at the output aperture of the microwave antenna was performed using an Agilent X-band waveguide calibration kit.

![Diagram of wireless microwave sensing system]

**Figure 4.36:** Schematic of wireless microwave sensing system.

Transmitting antenna was connected to the output port of PNA while the receiving antenna was connected to the amplifier and then fed on to the analog input port of the wireless sensor node. Krytar 604A was used as a detector which converted the received microwave signal into the corresponding voltage signal. The amplified output from the detector was then transmitted wirelessly to the receiving unit which consisted of a wireless base station connected to the computer. The LabVIEW program in the computer received the wireless data, displayed the voltage graph in GUI in real time and saved the data simultaneously.
Two different antenna combinations were used which were separated by a distance \( l \) mm. In the first combination, two open-ended rectangular waveguide antennas (OEWA) were used. The OEWA without flange (non-flanged OEWA) and output aperture dimension of 22.8 mm x 10.1 mm was used as a transmitting antenna while OEWA with flange (flanged OEWA) and output flange dimension of 41.1 mm x 41.1 mm was used as a receiving antenna. In the second combination, rectangular dielectric waveguide antennas (DA) fed by the OEWAs and end dimension of 22 mm x 9 mm were used. The picture of the first antenna combination consisting of flanged and non-flanged OEWA is shown in Fig. 4.37.

![Picture of the first antenna combination consisting of flanged and non-flanged OEWA](image)

**Figure 4.37:** Picture of the sensor including open-ended waveguide antennas, adapters and a detector.

A construction foam specimen with embedded rubber disc was used for the proof of concept. In this specimen, the rubber disk of diameter 32 mm and thickness 3 mm was embedded in the middle of the foam sample with a dimension of 225 mm x 225 mm x 8 mm. The specimen was moved between the transmitting and receiving antenna with a linear uniform motion along a single direction. This movement introduced the foam-rubber-foam section of the specimen at a constant time interval between the two antennas. The continuous wave microwave signal at a set frequency transmitted by the transmitting antenna passes through the specimen and received by a receiving antenna. The microwave signal received by the receiving antenna was then converted to the proportional dc voltage by using a detector. This voltage value was then amplified by an amplifier before feeding into the wireless sensor node for transmission.
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4.6.4 Results and discussion

Fig. 4.38 shows the received peak-to-peak voltage at the receiving unit from the first antenna combination for 10.3-GHz transmitting frequency and output power level of 0 dBm. A 5000 number of data was swept using the LabVIEW program. When the foam was introduced between the antennas during the linear motion, the peak-to-peak amplitude received by the receiving unit was ~ 1.64 V, and when the rubber was introduced between the antennas, the peak-to-peak dropped down to ~ 1.39 V. This is mainly due to the absorption of a microwave signal by the embedded rubber.

![Graph showing voltage amplitude over data sweep]

**Figure 4.38:** Peak-to-peak voltage at the receiving unit using the first antenna combination.

Next, the same process was repeated using the second antenna combination and the change in voltage due to the change in the dielectric property of foam and rubber was observed as shown in Fig. 4.39. The peak-to-peak amplitude obtained by receiving unit for foam was ~ 1.31 V and for rubber was ~ 1.19 V. However, from the above results, it was observed that the sensitivity of the first combination with OEWAs was higher compared to the second combination with DAs.
The peak-to-peak voltages obtained using the first and second combinations were normalised to unity to compare the sensitivity of OEWA and DA antenna combination and plotted as shown in Fig. 4.40.

From the figure, it is clear that OEWA has higher sensitivity compared to DA. For the same specimen with the same microwave parameters, OEWA changed by ~ 0.15 V.
while DA changed by ~ 0.09 V when foam and rubber were introduced subsequently between the antennas. The lower sensitivity of DA combination can be attributed to the loss of microwave signal from the interface where the DA is connected to the OEWA.

This shows that the proposed wireless microwave sensing system is able to detect microwave properties of the materials and provides a proof-of-concept for non-destructive testing of a variety of materials. Two different antenna combinations were able to detect the rubber disc embedded inside the foam accurately. However, the sensitivity of the first antenna combination with two OEWAs was higher than the second antenna combination with two DAs.

4.7 Summary

This chapter presented the near-field microwave imaging system for defect detection in planar construction materials and structures. The development of 3-axis multifunctional microwave imaging system was described. The system was developed using three separate modules which were integrated to form a single imaging system capable of interrogating a variety of materials with various dielectric properties. The backbone of the developed imaging system was a PNA which was used for microwave signal generation as well as the data acquisition. The generated microwave signal was transmitted and received via a microwave antenna which was attached to the 3-axis mechanical scanning system. The scanning system was capable of scanning along X-, Y- and Z- axis using a stepper motor based on the application and type of the specimen under investigation. The PNA and the scanning module was controlled from the control centre through a program developed using LabVIEW platform. The GUI of the developed program was made simple and convenient with the user only needing to input the scan area and step size of the area to be scanned. Further, raw microwave image of the scan area could be visualised in real time in GUI.

The transmitted microwave signal at a given frequency interacted with the specimen and reflected back. The reflected signal was then used to obtain the magnitude and phase of the reflection coefficient. Once, these parameters were obtained, signal and image processing was carried out to smooth and enhance the image to make it easier
to visualise the defects. The developed system was able to detect flaws in a variety of construction materials and structures. For the proof of concept, the specimens composed of these materials were interrogated which were broadly divided into three categories: metal-based composite materials, cement-based composite materials and dielectric materials to cover a broad range of materials that are being used in the construction industry. First, the specimens with planar geometry were investigated for flaws and hidden targets along scan plane 1. Scan plane 1 referred to the movement of scanner along X- and Y- axis only following the raster scan pattern which is a traditional scanning technique. Next, these specimens were tilted at a certain angle, and by accurately measuring the tilt angle and with the information about scan area, the Z-axis of the scanner was adjusted manually to follow the profile of the tilt along scan plane 2. The images obtained along scan plane 2 were then compared with the images obtained for tilted specimen scanned along scan plane 1. As expected, the images obtained along scan plane 2 were better with a prominent indication of flaws compared to images obtained along scan plane 1. Along scan plane 1, these flaws were masked because of the standoff distance change along the scan area. Despite the prominent indication of flaws along scan plane 2, the images were unclear and in some instances, their indications of flaws and targets were blurred near the boundary. These are mainly caused due to the inaccurate measurement of tilt and manual error. Overall, the imaging system was able to detect flaws in planar and tilted specimen accurately. However, there is a limitation with the current microwave imaging system regarding the structure with non-planar geometrical shapes. These problems can be solved using automatic adjustment of the Z-axis using laser displacement sensors for which a novel dual laser integrated imaging system is developed which are explained in detail in Chapter 5.

A wireless microwave sensing system has an advantage over conventional wired microwave sensing system mainly on two major aspects: (1) it greatly reduces the complexity of the microwave sensing system with fewer cables and connections and (2) it enables remote sensing of materials from longer range for real-world applications. These advantages make the use of wireless data acquisition system an attractive candidate in microwave non-destructive testing applications. A proof-of-concept was provided where a wireless data acquisition system was successfully
applied for determining the microwave properties of the material. The results prove that this technology can be used for non-destructive testing of a variety of materials. Further, the results demonstrate that the system can be used with a scanning mechanism to generate microwave images for different health monitoring applications.
Chapter 5 A Novel Dual Laser Integrated Imaging System for Non-destructive Testing of Non-Planar Structures

5.1 Introduction
This chapter presents a novel dual laser integrated microwave imaging system for non-destructive testing of construction materials and structures. A microwave imaging system was developed and tested for planar and tilted specimens in chapter 5. However, the system was not able to investigate the non-planar specimen. Moreover, most of the near-field microwave imaging system using open-ended probes as explained previously is not able to examine the non-planar specimen. A novel integrated sensing unit (ISU) has been developed that automatically follows the contour of the material under test at a constant standoff distance and generates microwave images. The developed system provides an economical and simpler solution that overcomes the current limitations of microwave imaging for non-destructive testing of structures with complex geometrical shapes and curvatures found in the real world. The detailed description of each module of the developed system along with the algorithm is demonstrated. The comparison between two different microwave antennas: dielectric waveguide antenna (DA) and open-ended waveguide antenna (OEWA) was performed to find the suitable antenna for the proof-of-concept of the developed system for the non-destructive testing of the non-planar specimen. The selected antenna is then used with the developed system to detect flaws in a variety of construction materials such as metals (surface breaking cracks and notches) and plasterboard. Finally, the summary with the discussion of the results and suitable recommendation of the antenna for non-destructive testing of non-planar structures using the developed system is also given.

5.2 Background
As discussed in the previous chapter, in a near-field microwave technique, a microwave antenna is scanned over a two-dimensional (2-D) scan area at some distance with the structure under test which is referred to as standoff distance[38]. The
microwave antenna irradiates the scan area, and the system generates microwave images using the reflected signal data. When the sample being inspected has a planar geometrical shape and is not tilted, the standoff distance remains constant, and a simple raster scan can be performed to generate these microwave images. Several studies have been reported where a simple raster scan was used to generate the microwave images in planar samples [140, 141]. In practice, structures are not always planar and might include curvatures, ramps, and uneven surfaces. Moreover, several factors such as sample surface roughness and bulging, undesired shaking/movement of the sample, the local relative tilt between the surface of the sample under test and the antenna may vary the standoff distance. This variation, in turn, significantly changes the properties of the microwave signal reflected from the sample. This change masks the indication of flaws such as cracks, debonds and delaminations [42, 163]. In particular, this is important for non-destructive testing of critical parts of civil infrastructures such as buildings, bridges, tunnels and dams which are geometrically complex and include connections, profiles and joints. Thus, during the scanning process, it is imperative either to compensate for the change in standoff distance or to keep the distance constant.

Several techniques have been used to compensate for the change in standoff distance. One of the methods uses spring-loaded potentiometer kept in contact with the specimen during the scan which generates a voltage proportional to the potentiometer resistance indicating the change in standoff distance [163]. This technique removes the non-contact feature from the microwave measurement technique, requires calibration and only compensates for a small range of standoff distance change. The small change in standoff distance due to surface roughness or bulging which are spatially smaller than the inspection area of the open-ended probe is not detected using this technique. Another method uses dual-polarised microwave reflectometer to automatically reduce the influence of standoff distance variation by producing two orthogonally polarised signals and a conditioning circuit to compensate for the standoff distance change [42]. However, the reflectometer design and the compensation algorithm are complex and applicable for a limited range of standoff distance change. A dual differential probe has also been designed based on two radiating apertures and a magic-T to coherently subtract the signals reflected from both apertures to compensate for standoff distance.
change [184]. Although the compensation range of the change in standoff distance is relatively wide, the design includes multiple components which affect the performance of the probe significantly at different frequencies. A simpler technique with differential probe based on a dual-loaded modulated single waveguide aperture has been developed which detects and subtracts the signals measured at two different aperture modulation states to remove the influence of standoff distance change [185]. However, the delay in switching between two electric field distributions might delay the scanning time.

On the other hand, studies to keep the standoff distance constant at hardware level has also been reported. A 3-axis scanning mechanism has been used to optimise a standoff distance that follows the contour of the surface of the specimen using the manual setting [186]. However, this method needs prior knowledge of specimen tilt for manually adjusting the change of standoff distance. The detailed description of this system is given in Chapter 4. Next, laser displacement sensor (LDS) was incorporated to the 3-axis scanning mechanism with microwave imaging system to provide automated control of the movement of the antenna attached to the scanner to follow the tilt of the specimen [187]. Although LDS is conventionally used in non-destructive testing of surface flaws in different materials, the integration of LDS with microwave imaging technique showed promising results [154, 155]. All of the aforementioned techniques used to compensate the change in standoff distance or to keep the distance constant are only applicable in the interrogation of the planar tilted specimens while the real structures can have various geometrical shapes and curvatures. The objective of this study is to overcome this limitation by developing a system capable of detecting flaws in specimens of different geometric shapes and curvatures with automatic adjustment of the standoff distance. For this purpose, a novel dual laser integrated microwave imaging system is proposed. The proposed system consists of a novel integrated sensing unit (ISU) with two LDSs and a single microwave antenna that provide an automated contour following over the specimen with different geometrical shapes at a constant standoff distance. Moreover, the proposed system does not require any calibration or complex compensation algorithm as the automatic contour following is performed with the simple algorithm at the hardware level.
5.3 Development of integrated imaging system

The integrated imaging system consisted of the integrated sensing unit (ISU), scanning unit, and the control and data acquisition unit as shown in Fig. 5.1. First, hardware in each unit was assembled, and an algorithm was developed for integration and synchronisation of these units [188]. The system was controlled through the GUI program developed on a LabVIEW platform on a monitoring computer.

![Block diagram of an integrated imaging system](image)

**Figure 5.1:** Block diagram of an integrated imaging system.

5.3.1 Integrated sensing unit

The integrated sensing unit consisted of a single microwave antenna and two laser displacement sensors designated LDS 1 and LDS 2 as shown in Fig. 5.2a. LDS 1 was positioned at a distance d1 from the microwave antenna along X-axis while LDS 2 was positioned at a distance d2 from the LDS 1 along Y-axis (cf. Fig. 5.2a (right)). Both distances d1 and d2 were adjustable based on the scan area and step size. However, the distance d2 should be arranged such that it exactly matches the step size of the scanner to get the accurate profile of the specimen.

Three different microwave antennas were used, namely, an X-band (8.2 GHz – 12.4 GHz) flanged open-ended rectangular waveguide antenna (OEWA) with output flange dimension of 41.1 mm x 41.1 mm (cf. Fig. 5.2b), OEWA with non-flanged open end (referred hereafter as non-flanged OEWA) with output aperture dimension of 22.8 mm x 10.1 mm (cf. Fig. 5.2c) and a rectangular dielectric waveguide antenna (DA) fed by OEWA with an end dimension of 22 mm x 9 mm (cf. Fig. 5.2d). A rectangular clear acrylic block was used as a DA. Non-flanged OEWA were used for non-planar specimens with high tilt or sharp edges for which the larger dimension of the flanged
antenna was incompatible. The microwave signal at a given frequency was transmitted through the antenna which irradiated the specimen in the near field. This transmitted signal (both magnitude and phase) was altered by the local dielectric and geometrical properties of the material of the specimen and reflected. The reflection coefficient, referenced to the antenna-aperture plane, was measured.

An LDS from Micro-Epsilon was used which consisted of a laser head and a detector. LDS uses the principle of optical triangulation where the distance is measured by angle calculation. In this measurement principle, a laser head projects a laser spot onto the specimen. The light is reflected and falls incident onto a detector at a certain angle depending on the distance. From the position of the light spot on the detector and the distance from the laser head to the detector, the distance to the laser spot is calculated [153]. The laser beam had a wavelength 670 nm and maximum output power of 1 mW.

**Figure 5.2:** Schematic of (a) integrated sensing unit (left) side view and (right) top view, and three antennas (b) flanged OEWA, (c) DA fed by OEWA and (d) OEWA with the non-flanged open end.
The measurement range of the LDS was from 60 mm to 260 mm. The diameter of the laser beam was 2.2 mm, and the range resolution was 0.1 mm. The detailed description of the working principle of LDS is given in Chapter 3.

For the near-field microwave measurement, the standoff distance should be relatively small. On the other hand, the smallest distance LDS could measure was 60 mm. For this reason, the LDSs were arranged above the level of microwave antenna such that the distance between LDS and specimen was always above 60 mm even when the microwave antenna was touching the surface of the specimen (cf. Fig. 5.2a (left)). This arrangement of ISU was used in all the measurements.

### 5.3.2 Scanning unit

The scanning unit comprised of components from National Instruments which included scan control unit, motion interface, drives and motors as shown in Fig. 5.3.

**Figure 5.3:** Block diagram of the scanning unit.
The detailed description of the 3-axis multifunctional scanning unit is given in Section 4.3.3. The same hardware for the scanning unit was used in this system as well. However, control of the scanning unit and the synchronisation of the scanning unit with the other modules of the system is carried out using a different algorithm developed using a LabVIEW platform which is explained in detail in Section 5.3.4. All three axes X-, Y- and Z- were used for the development of the integrated imaging system as the system required to follow the contour of the non-planar specimens.

5.3.3 Control and data acquisition unit

The control and data acquisition unit consisted of an Agilent N5225A performance network analyser (PNA) and a computer. The detailed description of the PNA and the measurement procedures are given in Section 4.3.1. The calibration of the setup at the output aperture of the microwave antenna was performed using an Agilent X-band waveguide calibration kit. PNA was connected to the computer through a GPIB interface. The PNA received the reflection coefficient from the microwave antenna and then sent to the computer through this interface. The computer was also responsible for data acquisition from the LDSs, controlling the movement of the scanners and initialising and synchronising ISU with the scanning unit through the developed LabVIEW program. Further, data processing and visualisation were also done on the computer.

5.3.4 Algorithm and GUI development

An object-oriented LabVIEW program was developed to control the PNA, to acquire data from the LDS and synchronise scanning unit and ISU. Further, GUI was developed to enable users to input the control parameters and to visualise the microwave image in real time. The block diagram showing working and synchronisation of the scanning unit and ISU is given in Fig. 5.4. The scanner was initialised by giving the scan area and the step size as an input. Simultaneously, PNA with the microwave antenna and both LDSs were initialised. The parameters given to PNA were scattering parameters (S-parameters), frequency range, number of data points collected in one sweep, system characteristic impedance, averaging number and trigger source. The parameters given to LDSs for initialisation were data output format type and measuring rate. After initialisation, microwave antenna started acquiring
reflection coefficient from the scan point and sent this data to the computer through PNA. After each acquisition, the stepper motor corresponding to X-axis started moving at a given step size.

Figure 5.4: Block diagram showing the working and synchronisation of the scanning unit and an integrated sensing unit.

LDSs and microwave antenna obtained data at each scan point along X-axis. During this movement, the displacement reading of LDS1 and LDS 2 were averaged and then subtracted to obtain a calibration distance (CD). A calibration distance is a measure by which the scanner should move the stepper motor corresponding to Z-axis to maintain constant standoff distance. The CD was then sent as a feedback to the control unit which commanded the scanning unit to move correspondingly along Z-axis. The scanner then continued raster scanning along X- and Y- axes till it reached the end of the scan area. A CD was re-calculated, and Z-axis adjustment was made after each scan point based on feedback from LDS1 and LDS2 so that the standoff distance was constant throughout. During this whole scanning process, microwave antenna
continued obtaining data, and then PNA sent the corresponding reflection coefficient to the computer. The flowchart of the workflow in the scanning unit and ISU is given in Fig. 5.5.

**Figure 5.5:** Flow chart showing the working of the scanning unit and an integrated sensing unit.

Once the computer received all the reflection coefficient values in a LabVIEW platform, data processing and visualisation were performed as shown in Fig. 5.6. The series of data at each alternate axis were flipped to compensate for the raster scan. The magnitude and phase data were then divided into the separate matrix and then mapped based on the step size and coordinate of the scan area. The real-time preview of the raw magnitude image could be seen in GUI. Further, MATLAB was used for smoothing and interpolation of the magnitude images. The smoothing was done by selecting a suitable gradient for proper grayscale representation, and the interpolation was done to enhance the image. Further, filters such as Savitzky-Golay filter was used in some images for further smoothing and enhancing the image. Thus, microwave images were generated for investigating the scan area of the specimen.
Figure 5.6: Block diagram for data processing and visualisation of the microwave signal.

Savitzky-Golay filters are a least-square smoothing filter which is based on least square polynomial approximation [178]. In the Savitzky-Golay approach, each successive subset of \((2m + 1)\) points is fitted by a polynomial of degree \(p\) \((p \leq 2m)\) in the least-square sense. The \(d\)th \((0 \leq d \leq P)\) differentiation (zeroth differentiation = smoothing) of the original data at the midpoint is obtained by performing the differentiation on the fitted polynomial rather than on the original data. Finally, the running least-square polynomial fitting can be simply and automatically performed by convolving the entire input data with a digital filter of length \((2m + 1)\). The convolution coefficients can be obtained for all data points, all polynomial degrees, and all differentiation orders but with only an odd number of data sets. The general filter equation of the Savitzky-Golay filter is given by [189]:

\[
g_i = \sum_{n=-n_L}^{n_R} c_n f_i + n \quad (5.1)
\]

where \(g_i\) is the output of the Savitzky-Golay filter; \(nL\) and \(nR\) are the number of points used to the left and the right of the data point, respectively.

5.4 Specimens

Three different specimens were used in this investigation to illustrate the applicability of the system for non-destructive testing of non-planar construction materials. The first specimen was made up of two 150 mm x 150 mm x 20 mm metal slabs with 1-mm crack/notch between them as shown in Fig. 5.7a. The plates were covered with two different dielectric covers – 12 mm thick plasterboard and 3.5 mm thick rubber sheet.
To simulate the notch, the metal plate was used beneath the metal slab while to simulate the through-crack condition; the metal plate was removed. The specimens were tilted at 10° during the test.

![Diagram of specimen 1 and specimen 2](image)

**Figure 5.7**: Picture of (a) specimen 1 and (b) specimen 2.

To prepare the second specimen, timber slabs were first used to make a sturdy triangular base with a slope of 30° on both sides. Then two 150 mm x 150 mm x 20 mm metal slabs were placed on each side of the slope of the timber base with 1-mm through-crack between them as shown in Fig. 5.7b. Two different dielectric covers were used – paper sheets (with thickness 0.6 mm) and 3.5 mm thick rubber sheet. Paper sheets were used to simulate a paint coating on the metal surface.

The third specimen was stepped plasterboard with a strip of rubber patch running through the middle of the specimen as shown in Fig. 5.8. Plasterboard is commonly used in internal wall and ceiling lining board in residential and commercial construction while rubber is commonly used as dampers in expansion joints and bridge bearings. The specimen represents a plasterboard wall with a dry lining rubber insulation. The stepped plasterboard specimen was prepared by stacking the layers of 10 mm thick plasterboards of varying width. The dimension of each step was 250 mm
x 19 mm, and the dimension of the rubber patch at each step was 18 mm x 18 mm x 1.5 mm.

Figure 5.8: Picture of specimen 3 tested by ISU with non-flanged OEWA.

5.5 Results and discussion

First, the comparison between flanged OEWA and DA antennas on crack detection was carried out on specimen 1. Based on this result, a suitable antenna was chosen to give the proof-of-concept of the proposed imaging system in the non-planar specimen. The scan was performed along two scan planes: scan plane 1 and scan plane 2 and the images were compared. Scan plane 1 refers to the raster scan without standoff distance optimisation i.e. without adjusting the Z-axis according to the CD while scan plane 2 refers to the scan with adjusted CD and constant standoff distance throughout the scan area.

5.5.1 Comparison between OEWA and DA antenna

The schematic of the experimental setup to compare the flanged OEWA and DA antenna in specimen 1 is shown in Fig. 5.9. OEWA and DA antennas were consecutively used inside ISU for this experiment. Specimen 1 with plasterboard and rubber coverings were tilted at 10°, and 1-mm through-crack and notch were investigated. At scan plane 1, the standoff distance $d$ changed while at scan plane 2, the standoff distance $d_0$ remained constant throughout the scan area. The step size was set at 3 mm, and the scan area was chosen to be 45 mm x 90 mm.
Fig. 5.10 shows the 10.3-GHz raw magnitude images of the scan area of specimen 1 with through-crack covered with plasterboard at both scan planes using flanged OEWA (cf. Fig. 5.10a) and DA (cf. Fig. 5.10b), respectively.

Figure 5.9: Schematic of specimen 1 with ISU.

Figure 5.10: Microwave images of the scanned area of specimen 1 with through-crack covered with plasterboard at (left) scan plane 1 and (right) scan plane 2 using: (a) flanged OEWA and (b) DA.
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There was no indication of through-crack at scan plane 1 using both antennas which were masked by the gradual intensity change due to variable standoff distance. At scan plane 2, through-crack could be observed using both antennas. However, an image obtained using flanged OEWA showed some indication of reflected microwaves from edges of metal through the plasterboard while there was no such indication using DA and the through-crack could be prominently observed.

The 10.3-GHz raw magnitude images of the scan area of specimen 1 with through-crack covered with rubber sheet at two scan planes using both antennas are shown in Fig. 5.11.

![Microwave images of the scanned area of specimen 1 with through-crack covered with rubber sheet at (left) scan plane 1 and (right) scan plane 2 using: (a) flanged OEWA and (b) DA.]

With flanged OEWA, there was a faint indication of through-crack even at scan plane 1. However, at scan plane 2 both antennas showed prominent indication of the through-crack. The clear images are obtained mainly due to the absorption of reflected microwaves by rubber layer. The absorption of the microwave signal by the rubber...
layer is mainly due to its high permittivity and dielectric loss property. Contrary to the previous case, the through-crack is more evident in the image obtained using flanged OEWA compared to DA.

Next, 10.3-GHz raw magnitude images of the scan area of specimen 1 with notch and covered with plasterboard was generated using both antennas as shown in Fig. 5.12. The images at scan plane 1 did not show any indication of the notch. At scan plane 2, both antenna showed indication of the notch with flanged OEWA showing the indication of the reflected microwave from the edges of metal as well. The indications, however, were not as clear as the indication of through-crack in the previous test. Also, it was observed that the values of reflection coefficients were negative. The negative values of reflection coefficient are due to the phase difference between the incident wave on the surface and the reflected wave from the surface.

![Microwave images of the scanned area of specimen 1 with notch covered with plasterboard at (left) scan plane 1 and (right) scan plane 2 using: (a) flanged OEWA and (b) DA.](image)

**Figure 5.12:** Microwave images of the scanned area of specimen 1 with notch covered with plasterboard at (left) scan plane 1 and (right) scan plane 2 using: (a) flanged OEWA and (b) DA.
The 10.3-GHz raw magnitude images of the scan area of specimen 1 with notch covered with rubber sheet using both antennas are shown in Fig. 5.13. The indication of the notch was clearer with both flanged OEWA and DA compared to the plasterboard covering. However, the indication was prominent with DA compared to flanged OEWA.

From the above results, it is clear that flanged OEWA gives clear indication of through-cracks while DA gives a clear indication of the notch. The electric field is concentrated within the slab in DA and having a smaller probe aperture; it was expected that it would give higher spatial resolution and consequently give a better indication of flaws. However, the higher standoff distance (>5mm) reduced the radiation efficiency of DA especially in layered specimens which did not strongly scatter the incident microwave signal. The indication of notches was weaker compared to through-crack which can also be attributed to the weaker scattering of microwave signal due to the interaction.
of the signal from the side and bottom of the notch which resulted in small variation in the magnitude of the reflection coefficient.

Further, the images from the flanged OEWAs showed indication of the internal structure of dielectric materials making it a suitable candidate for defect detection in layered specimens. Since different layered non-planar specimens are used for the proof-of-concept of the developed system, OEWAs are chosen. However, the large aperture size of the flanged OEWAs makes it incompatible for near-field inspection of complex non-planar specimens with high tilt or sharp edges. The flange tends to touch the surface of the specimen during the inspection. Due to this reason, non-flanged OEWAs are used in ISU for further investigation of the non-planar specimen.

5.5.2 Detection of flaws in the non-planar specimen
The schematic of specimen 2 being tested by ISU at both scan planes is shown in Fig. 5.14.

![Diagram of specimen 2 with ISU](image)

**Figure 5.14:** Schematic of specimen 2 with ISU: (a) side view and (b) top view (not to scale).
Due to the presence of two slopes, ISU had to first move up (positive Z-axis) and then down (negative Z-axis) to keep the standoff distance constant. The scan area at each slope was chosen to be 45 mm x 90 mm with 3 mm step size. The 10.3-GHz raw magnitude images of the scan area of specimen 1 covered with paper sheet were generated as shown in Fig. 5.15. From the images, it is evident that the indication of through-crack is masked by variable standoff distance along scan plane 1. However, at scan plane 2, the gradual intensity changes significantly decreased, and there was an indication of through-crack in both slope 1 and slope 2. Although the indication of through-crack was prominent, there were faint lines along the scan area. It is attributed to the standoff distance variation along the thickness of the output aperture of the non-flanged OEWA antenna due to a high tilt angle (30º) of the specimen.

![Microwave images of the scanned area of specimen 2 covered with paper along (left) slope 1 and (right) slope 2 at (a) scan plane 1 and (b) scan plane 2.](image)

**Figure 5.15:** Microwave images of the scanned area of specimen 2 covered with paper along (left) slope 1 and (right) slope 2 at (a) scan plane 1 and (b) scan plane 2.

Next, raw magnitude images with rubber sheet covering were generated as shown in Fig. 5.16. Similar to the previous case, scan plane 2 showed prominent indication of through-crack along both slopes, but the effect of standoff distance variation due to the thickness of the output aperture of the non-flanged OEWA could be observed as faint lines.
Figure 5.16: Microwave images of the scanned area of specimen 2 covered with rubber along (left) slope 1 and (right) slope 2 at (a) scan plane 1 and (b) scan plane 2.

The next specimen was a stepped plasterboard specimen with rubber patches on top referred to as specimen 3. The prime purpose of this test was to investigate the feasibility of the developed imaging system in a complex shaped specimen with sharp corners. The schematic of the specimen 3 being tested by ISU is shown in Fig. 5.17. Contrary to the previous tests, where scanner was moving ISU diagonally, here, the scanner moved ISU along the steps maintaining constant standoff distance throughout in scan plane 2. The scan area was chosen to be 90 mm x 171 mm with a step size of 3 mm.
Figure 5.17: Schematic of specimen 3 with ISU: (a) side view and (b) top view (not to scale).

Fig. 5.18 shows the 10.3-GHz filtered magnitude image of the scan area of the specimen 3 at both scan planes. Savitzky-Golay filter was used to smooth the raw magnitude images. At scan plane 1, there is an indication of the rubber patch only at the middle of the scan area where the standoff distance was constant at the top of the step (cf. Fig. 5.18a). However, there was no indication of the patch elsewhere due to the change in standoff distance. However, at scan plane 2, there was a clear indication of rubber patch throughout the middle of the scan area (cf. Fig. 5.18b).
Figure 5.18: Microwave images of the scanned area of specimen 3 (centre) at (a) scan plane 1 and (b) scan plane 2.

The results show that the proposed imaging system could accurately optimise the standoff distance in non-planar specimens at the hardware level without the need for complex signal processing. The two LDSs were able to give accurate information about the profile of the specimen under test, and thus the system was able to maintain constant standoff distance throughout the scan in different specimens.

5.6 Summary

Most civil infrastructures consist of structural members with different geometrical shapes and sharp edges. The non-destructive testing of these structures is a challenging task using microwave imaging techniques mainly because of the need to maintain the constant standoff distance during the scanning process or to compensate for the standoff distance change. To overcome this limitation, a novel dual laser integrated microwave imaging system has been developed. The detailed description of the different modules and their synchronisation algorithm is given. The system was developed by using most of the hardware from the microwave imaging system developed in Chapter 4 with an addition of two LDSs. However, the algorithms and synchronisation principle were novel.

The developed system was able to automatically trace the contour of the surface of the material under test during the scanning process at a constant standoff distance and generate microwave images. In this study, OEWA was used to demonstrate the
applicability of the system to non-contact detection of flaws in metal and dielectric targets embedded in layered structures. Moreover, a variety of construction materials with complex geometrical shapes and different flaws were used to illustrate the flexibility of the system. The specimens were selected with diverse dielectric properties. These specimens included metal and dielectric based composite materials and layered structures. The developed system was able to interrogate flaws in all these specimens accurately, and the quality of images was comparable to the images obtained using planar specimens in Chapter 4.

The developed system is robust and gives real-time information of any flaws on the structure without the need for complex image processing. The standoff distance optimisation techniques in literature demonstrated the application only in slanted metal specimens and required additional time to optimise the distance [184, 185]. However, the developed system can be used for the non-destructive testing of a variety of construction materials and structures in real-world applications with varied geometrical shapes. Moreover, the developed system is able to generate images in real time for damage visualisation. With the development of this system, the inadequacy of current microwave imaging system becomes less of a limiting issue, and the system can be a one-stop solution for interrogation and analysis of wide range of structures used in civil, mechanical and aerospace industry.
Chapter 6 Piezoelectric Sensing for Interfacial Defect Detection in Concrete Based Composite Structures

6.1 Introduction
This chapter presents a methodology for interfacial defects in concrete based composite structures. The methodology is based on a simple piezoelectric pitch-catch technique with a single actuator and a single sensor which are attached to a single side of the composite structure. The generated signal is transmitted via an actuator to the structure and received by a sensor placed at some distance from the actuator. The received signal is then utilised to analyse the interfacial defects such as gaps and debonding. A brief background on piezoelectric sensing technique and the hardware used for the application has been provided. Next, the measurement approach and description of the specimens are given. The measurement technique is then utilised for gap detection between metal/concrete and CFRP/concrete. Further, debonding of size less than 1 mm between concrete and CFRP is detected. The variety of debondings such as lengthwise debonding, widthwise debonding and patch debonding were investigated. The statistical indexes are introduced and employed to quantify the extent of gaps and debonds. Finally, a summary of results and detailed analysis is performed.

6.2 Background
The piezoelectric effect occurs in certain crystalline minerals when they become electrically polarised on the application of mechanical force. These crystals undergo two effects: direct effect and converse effect. In direct effect, tension and compression generate voltages of opposite polarity and in proportion to the applied force. In converse effect, crystal when exposed to an electric field, lengthens or shortens according to the polarity of the electric field and in proportion to the strength of the field. Due to this reason, piezoelectric materials are labelled as smart materials as they can generate a surface charge in response to applied mechanical stress. Conversely, they undergo a material deformation in response to an applied electric field. This unique capability enables the piezoelectric material to be used as both sensor and actuator. Traditionally, piezoelectric materials have used in a variety of applications.
Piezoelectric materials were used in accelerometers, strain sensors [190], pressure sensors [191], emitters and receptors of stress waves [192], vibration sensors [193] and actuators [194]. The advantage of the piezoelectric technique includes high sensitivity to incipient damages, economical, simple and immunity to low-frequency noises.

The most common technique of NDT is the electromechanical impedance technique where the damage detection is based on a comparison of the received signal with the reference signal. The change in the signal characteristic would effectively suggest the deterioration of the state of health of the structure. However, several factors such as electrical interference, ageing of structure, temperature fluctuations and mechanical vibrations could also lead to change in these signals.

An electromechanical model which quantitatively describes the process is presented in Fig. 6.1. Assuming that an axial piezoelectric transducer (PZT) actuator is attached to one end of a single degree-of-freedom (DOF) mass-spring system, whereas the other end is fixed, Liang et al. (1994) showed that the electrical admittance \( Y(\omega) \), which is an inverse of the electrical impedance, of the PZT actuator is a combined function of the mechanical impedance of the PZT actuator \( Z_a(\omega) \) and that of the host structure \( Z(\omega) \) [195].

\[
Y(\omega) = \frac{I}{V} = i\omega a\left(\varepsilon_{53}^T - \frac{Z(\omega)}{Z(\omega) + Z_a(\omega)}d_{53}^E x_{xx}\right)
\]  

(6.1)

where \( V \) is the input voltage of the PZT actuator, and \( I \) is the output current from the PZT. \( a, d_{53}, \varepsilon_{53}^T \) and \( x_{xx} \) are the geometry constant, the piezoelectric coupling constant, Young’s modulus, and the complex dielectric constant of the PZT at zero stress, respectively and \( \omega \) is the angular frequency. Fig. 6.2 shows the geometric representation of the forces affecting a piezoelectric element which demonstrates the nomenclature of the constants used in the equation above. Since a piezoelectric ceramic in anisotropic in nature, these constants relate to both the direction of the applied electric or mechanical force and the direction perpendicular to these forces. As a result, each constant has two subscripts that indicate the direction of the two related quantities. Direction X, Y, or Z is represented by the subscript 1, 2, or 3, respectively, and shear about one of these axes is represented by the subscript 4, 5, or 6, respectively where the direction of positive polarization coincides with the Z-axis.
Equation 6.1 sets the groundwork for using the PZT actuator for structural health monitoring applications. Assuming that the mechanical property of the PZT does not change over the monitoring period of the host structure, the above equation clearly shows that the electrical impedance of the PZT is directly related to the mechanical impedance of the host structure, allowing the monitoring of the host structure’s mechanical properties using the measured electrical impedance. Consequently, any changes in the electrical impedance signature can be considered an indication of changes in the structural integrity [196].

**Figure 6.1:** One dimension model used to represent a PZT-driven dynamic structural system.

**Figure 6.2:** Geometric representation of forces affecting a piezoelectric element.
6.2.1 Selection of frequency range

In the piezoelectric technique, the excitation frequency is typically in kHz range so that the wavelength of the resulting stress wave is smaller than the typical size of the defect to be detected [197]. The most common frequency range for this technique ranges from 30 kHz to 400 kHz for PZT patches of 5 to 15mm in size [196]. The sensing radius increases with the frequency. To localize the sensing range, frequencies greater than 200 kHz are normally utilized. However, frequencies greater than 500 kHz are unfavourable for damage detection because the sensing region of the PZT patch becomes small and the PZT show high sensitivity to own bonding condition rather than any damage to the monitored structure. On the other hand, large sensing region is covered by a lower frequency range which affects the sensitivity of the technique. Piezo-impedance transducers do not behave well in a frequency less than 5 kHz and lose its utility entirely below 1 kHz [198].

The piezoelectric system typically consists of piezoelectric transducers bonded to the structure under test and a signal generator and interrogator. For this study, a commercial piezoelectric sensor package, ScanSentry was used for signal generation and data acquisition.

6.2.2 Commercial sensor package ScanSentry

ScanSentry is the diagnostic hardware platform for SHM. The package consists of piezoelectric actuator/sensor network in the form of a layer called SMART LAYER, signal generation and data acquisition hardware called SMART suitcase and data processing, visualisation and analysis software called In-Sight. The front panel of ScanSentry signal generation and data acquisition hardware is shown in Fig. 6.3. ScanSentry is a compact and lightweight SHM package with easy-cable connection and diverse features. The specifications of ScanSentry are as follows [199]:

i. Integrated arbitrary waveform generator that can generate a waveform from a frequency of 10 kHz up to 700 kHz.

ii. Waveform generator with default memory size of 1024 samples which is expandable up to 4096 samples.
iii. An integrated power amplifier that can output a maximum of ± 47 V to a PZT actuator.
iv. Support for up to 16 dedicated PZT actuators and 16 dedicated PZT sensors.
v. The data acquisition sampling rate of up to 48 MHz.
vi. Data acquisition resolution of 12 bit and analog to digital converter input range of ± 1 V.
vii. Support for temperature measurement sensor such as resistance temperature detector (RTD).
viii. Battery powered and able to provide 110 V/220 V AC through the adapter.
ix. Operation temperature: 0° C to 45° C.
x. USB 1.1/2.0 interface with the monitoring PC.

Figure 6.3: Front panel of ScanSentry signal generation and data acquisition system [199].

6.3 Measurement approach
The measurement system consisted of two piezoelectric transducers, signal generation and data acquisition unit and a computer as shown in Fig. 6.4. Each piezoelectric transducer disc had a diameter of 6.35 mm and a resonant frequency of 300 kHz in a radial mode. One piezoelectric transducer was used as an actuator (A1), and another as a sensor (S1) and they were attached to the external surface of conducting side (metal or CFRP) of the concrete-based specimen at a distance of l from each other. Both piezoelectric transducers were connected to a signal generation and data acquisition unit. A computer was connected to the signal generation and data acquisition unit through which the command for signal generation and data acquisition was given. A sine burst signal with 5 peaks was used as an actuation signal with a peak-to-peak amplitude of 8 V. To select a suitable excitation frequency, the frequency
Chapter 6

sweeps from 100 kHz to 500 kHz at a step size of 100 kHz was done. The received signal had the highest amplitude at a frequency of 300 kHz which matched the resonant frequency and was used as an excitation frequency. The generated wave propagated along the conducting plate and received by the sensor at no gap (reference) and various gaps between the metal/CFRP and concrete surface for gap detection. Similarly, the changes in the received signal at the computer were used to determine the presence of debonding between CFRP plate and concrete by analysing the signal obtained at no damage and various debonding. The sampling rate of 48 MS/s was used for data acquisition, and the gain of 40 dB was applied to the signal received by the sensor. This signal was then sent to the computer where the data was saved for comparison and statistical analysis.

![Figure 6.4: Schematic of the experimental setup of a piezoelectric sensing system for interfacial defect detection.](image)

**6.4 Detection of the gap in concrete-metal composite structures**

Concrete-metal composite structures such as concrete-filled steel tubes (CFSTs) are abundantly used in civil infrastructures due to their higher load-carrying capacity, good ductility, low strength degradation and energy absorption capability under excitations such as earthquake [200, 201]. This type of composite structures requires shear force transfer between metal and concrete surfaces so that the compressive strength of core concrete can be increased due to lateral confinement from metal and local buckling of metal can be restrained by the concrete [202, 203]. The poor construction quality,
shrinkage of concrete, temperature variations are some of the factors which may lead
to a gap between metal and concrete [204]. This gap reduces compressive and flexural
behaviour of the composite structure and decreases the load carrying capacity and
ductility [205]. Such gaps cannot be visually identified, and a proper detection
technique is needed.

Several techniques have been reported for detecting the gaps in composite structures
such as CFSTs. Near-field microwave sensors have been proposed and applied to
detect gap value of over 0.5 mm between metal and concrete [177, 206]. However, this
technique required drilling small holes in the metal for sensor installation which might
affect the structural properties of the concrete-metal composite structure. Piezoelectric
sensors have been conventionally used in different health monitoring applications [65,
193]. The application of piezoelectric sensors for gap detection in composite structures
has been limited especially in concrete-metal composites. Piezoelectric discs were
used as sensors and actuators in a pitch-catch mode which were bonded to a steel bar.
The steel bar was cast into a concrete beam. This embedded piezoelectric sensing
technique detected gaps of 2.5 mm between steel bar and concrete beam [207, 208].
Embedded piezoelectric sensors were used to detect debond between steel rebar and
cement by analysing the change in wave propagation properties [69]. For this
purpose, concrete-steel interface spectral element was developed for quantitative
analysis of debonding. Piezoelectric sensor techniques have been used to detect a gap
between steel and concrete in CFSTs [209, 210]. For this purpose, Smart Aggregate
(SA) consisting of piezoceramic patch inside a protective material was embedded
inside concrete and used as an actuator while several piezoelectric patches were
attached to the external surface of steel and used as sensors. Wavelet packet analysis
was carried out to detect the gap. The application of this technique in practice is
questionable since the SA should be embedded inside concrete and its sensitivity is
low: detected gap had a value of 4 mm which is too large.

In this section, the piezoelectric sensor technique is proposed to overcome the
limitation of existing piezoelectric technique for gap detection between concrete and
metal [211]. The proposed technique uses piezoelectric transducers (both actuators and
sensors) attached to the external surface of the metal. Three statistical indexes have
been applied for quantitative analysis of the gap. The proposed technique is fully non-invasive, external and one-sided as will be described in the next section.

### 6.4.1 Methodology and specimens

The schematic of the experimental setup to detect a gap in the concrete-metal composite structure is shown in Fig. 6.5. Multiple measurements were taken with no gap and the average of these voltage measurements vs time was considered as a reference signal. The average voltage signal with gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were taken, and the difference between these average signals indicated the presence of the gap. Then, the standard deviation was determined to test the repeatability of the proposed technique.

![Figure 6.5: Schematic of the experimental setup for detection and monitoring of gap between metal and concrete using piezoelectric transducers: an actuator (A1) and sensor (S1).](image)

For this study, specimens based on a 250 mm x 250 mm x 250 mm concrete block were used. A metal plate was placed on top of this concrete block, and the arrangement of the block and each plate without a gap and with different gap values were provided as shown in Fig. 6.6. Paper sheet with a thickness of 0.1 mm was placed on the edges between the metal plate and concrete block to provide a gap. Concrete block with a 6-mm thick steel plate (cf. Fig. 6.6a) was referred to as concrete-metal 1 and with 1.6-mm thick aluminium plate (cf. Fig. 6.6b) was referred to as concrete-metal 2. The
relatively thick steel plate was chosen because it is commonly used in a composite structure with concrete such as CFSTs while the aluminium plate was used for comparative analysis of the proposed technique with a thin metal plate. The steel plate had a dimension of 297 mm x 270 mm, and the aluminium plate had a dimension of 600 mm x 450 mm.

![Steel plate and Concrete block](image)

(a)

![Aluminium plate and Concrete block](image)

(b)

**Figure 6.6:** Picture of the transducers testing specimens (a) concrete-metal 1 and (b) concrete-metal 2.

### 6.4.2 Results and discussion

The first 5 measurements were taken with no gap in concrete-metal 1 where the steel plate was directly in contact with the concrete. The average of these 5 voltage measurements vs time was considered as a reference signal as shown in Fig. 6.7a. Then, the average voltage signal of 5 measurements with gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were taken respectively as shown in Figs. 6.7b-e. There was a difference between the average reference signal and average signals with a gap which indicated the presence of the gap.

The standard deviation was determined for 5 measurements for each case. The maximum standard deviation of the reference signal over time was determined to be
Similarly, the maximum standard deviation for gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were 0.07, 0.02, 0.02 and 0.02, respectively. It should be noted that standard deviation at no gap and a small gap is relatively higher than the others. It can be attributed to measurement error due to the roughness of concrete surface and non-planarity of the metal plate.

**Figure 6.7:** Average output voltage vs time at different values of gap in concrete-metal 1: (a) 0 mm (reference), (b) 0.1 mm, (c) 0.2 mm, (d) 0.3 mm and (e) 0.4 mm.

For quantitative analysis of the results, different statistical indexes were used. The first index was the correlation coefficient determined between the average reference signal and the average signal at each gap and plotted as shown in Fig. 6.8a. It can be seen from the plot that the correlation coefficient decreases with increasing gap value which shows that the dissimilarity between the reference signal and signal with gap
increased. Further, linear fitting was carried out. The coefficient of determination ($R^2$) was determined to be 0.95 which imply that the corresponding gap can be predicted from this fitted curve.

The second index was a peak-to-peak (P2P) amplitude. To get P2P amplitude, the resultant signal was obtained at each gap value by subtracting the average signal at different gap values against the average reference signal. The P2P amplitude of this resultant signal was plotted, and linear fitting was done as shown in Fig. 6.8b. It is clear from the graph that the P2P amplitude increases with increasing gap. For P2P amplitude, $R^2$ was determined to be 0.91.

**Figure 6.8:** Statistical indexes at different values of the gap in concrete-metal 1: (a) correlation coefficient and (b) change in peak-to-peak (P2P) amplitude of the resultant signal with the fitted curve.

A similar experiment was conducted to detect the gap in concrete-metal 2. The average reference signal is shown in Fig. 6.9a while the average signals with gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm are shown in Figs. 6.9b-e. Similar to the previous case, there is a difference in signal with gap compared to the reference signal which indicated the presence of the gap. The standard deviation was also determined for 5 measurements for each case. The maximum standard deviation of the reference signal over time was determined to be 0.13. Similarly, the maximum standard deviation for gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were 0.10, 0.11, 0.11 and 0.08, respectively. Similar to the previous case, the maximum standard deviation was obtained at no gap which is mainly due to the roughness of the concrete surface.
However, the standard deviation values were higher compared to the concrete-metal 1. It is mainly because of the measurement error during experimental setting of the thin aluminium plate.

![Figure](image)

**Figure 6.9:** Average output voltage vs time at different values of gap in concrete-metal 2: (a) 0 mm (reference), (b) 0.1 mm, (c) 0.2 mm, (d) 0.3 mm and (e) 0.4 mm.

The correlation coefficients between the average reference signal and the average signal at each gap values were determined and plotted as shown in Fig. 6.10a. It can be observed from the figure that the correlation coefficient decreases with increasing gap in aluminium plate as well. Linear fitting was done, and $R^2$ was determined to be 0.85. Then, the P2P amplitude of the resultant signal was plotted, and the linear fitting was done as shown in Fig. 6.10b which clearly shows that the P2P amplitude increases with increasing gap. For P2P amplitude, $R^2$ was determined to be 0.86.
The third index used to quantify the gap was root-mean-square-deviation (RMSD). Fig. 6.11 shows the RMSD at different gaps for concrete-metal 1 and concrete-metal 2. For concrete-metal 1 (c.f., Fig. 6.11a), the RMSD values were 0.46, 0.52, 0.55 and 0.56 for 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm gap values, respectively. The increasing gap provided larger RMSD value. These RMSD values can be correlated with the gap values and can be used as a gap value index. For concrete-metal 2 (c.f. Fig. 6.11b), RMSD values were 0.55, 0.69, 0.84 and 0.86 for 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm gap values, respectively, which also show significant correlation with the gap values.

**Figure 6.10:** Statistical indexes at different values of the gap in specimen 2: (a) correlation coefficient and (b) change in peak-to-peak (P2P) amplitude of the resultant signal with the fitted curve.

**Figure 6.11:** RMSD values at different values of gap for: (a) concrete-metal 1 and (b) concrete-metal 2.
The above results show the applicability of the piezoelectric sensing system for gap detection between metal and concrete. Statistical analysis showed that the correlation coefficient and P2P amplitude changed with changing gap value. The high value of $R^2$ of the fitted curve implied that it could be used for measurement of gap value. The statistical analysis also showed that the gap values could be correlated quantitatively with RMSD values.

### 6.5 Detection of the gap and debonding in concrete-CFRP structures

Fibre reinforced polymer composites have been used for external bonding of concrete members for strengthening concrete structures [212-215]. The most common composites used for this purpose are carbon fibre reinforced polymer (CFRP) laminates and plates. The CFRP composites are light with high resistance to corrosion and can be applied using relatively simple technology, for instance, external bonding of FRP plates or laminates to the concrete surface [212, 213]. Other applications of CFRP composites is concrete-filled CFRP tubes [214], and reinforced concrete beam-column joints strengthened with CFRP jacketing [215]. However, the poor construction quality, aging, shrinkage of concrete, deterioration due to moisture may cause flaws such as debonding and gap between CFRP composites and concrete surfaces [216]. These flaws significantly degrade the structural integrity and safety of the concrete structure strengthened with CFRP composites, and they cannot be visually identified in many cases. Therefore, advanced techniques for NDT of CFRP-strengthened concrete structures are in demand.

Several NDT techniques have been developed and applied for detecting the gaps and debondings between CFRP composites and concrete. Recently, an impact-echo method has been applied to detect debonding flaws at the epoxy-concrete interfaces in near-surface mounted CFRP strengthening beams [216]. However, this method needed an external impact source. Acoustic-laser technique was also used to detect gaps in CFRP bonded concrete structure by vibrating the target with an acoustic excitation and characterising the vibration behaviour with laser beam [217]. The method is particularly suitable for detecting the air voids near the surface of CFRP since the size of the artificial defect used in this study was 50 mm × 50 mm × 30 mm. Pulsed infrared thermography method was used for inspection of CFRP-concrete composites beams
[218], but this method required artificial heating in a laboratory which applicability in practice is questionable. A dual polarised near-field microwave reflectometer was proposed and applied for detecting debond between CFRP laminates and concrete in the lab and an actual bridge using two-dimensional images of the structure under test [42]. However, this technique needed bulky mechanical systems such as scanners to perform raster scanning of the antenna over the specimen under test.

The application of the piezoelectric technique for gap/debond detection in CFRP-concrete composite structures has been limited. Piezoelectric techniques have an advantage over conventional health monitoring techniques for debond detection mainly because of their lightweight, low cost, high bandwidth and active sensing features [219]. Further, the transducers come in a variety of forms which can easily be attached to the target structures. These techniques are conventionally used for the detection of cracks and stresses on the reinforced concrete structures [220, 221]. The piezoelectric transducers used for this purpose are generally embedded inside the concrete during the concrete casting. One such embedded sensor technique was used to detect debonds between the concrete and the embedded steel rebar [207]. The analysis of wave propagating along the structure using numerical computational techniques is another method of damage detection such as debondings. Finite element methods are generally used to investigate the wave characteristics in time domain [208] while spectral element methods are used for the analysis in frequency domain [222]. Guided wave propagation and spectral element method were used to detect interfacial defects in the concrete-steel interface where steel rebar was embedded inside the concrete [69]. In this technique, the spectral model was developed and a numerical simulation was carried out [223] which was verified using experimental measurements. However, in all above techniques, the sensors needed to be embedded into the concrete to detect the defects which require a special preparation of the structures. Another piezoelectric based technique used statistical analysis method to detect interfacial defects in concrete-steel interface[211]. An electro-mechanical impedance-based technique for identification of the debonding conditions of a CFRP laminated reinforced concrete beam using PZT ceramic patches was proposed in [224]. This technique demonstrated promising results but could only detect debonding near the patches at a small area.
An advanced piezoelectric based sensor technique is used for detection of a gap between a CFRP plate and early-age concrete surfaces in this section. The proposed technique uses the propagation properties of the guided waves in the CFRP plate excited and received by piezoelectric transducers attached to the external surface of the plate attached to the concrete specimen.

### 6.5.1 Specimens

The specimens for the gap detection investigation included early-age concrete structure and two different CFRP plates. These specimens were based on a 200-mm concrete cube, and a CFRP plate was attached to the cube without and with a gap between the surfaces of the cube and plate as shown in Fig. 6.12a. The gaps of different values were arranged using paper sheets, as spacing. One specimen included a 5-mm thick CFRP plate with the dimension of 240 mm x 100 mm (referred to as concrete-CFRP 1) while another specimen included a 2-mm thick CFRP plate with the dimension of 150 mm x 50 mm (referred to as concrete-CFRP 2). Concrete cube was prepared by mixing cement, sand, coarse aggregates and water, and placed inside the mould for casting. In the experimental investigation, a CFRP plate was placed on top of this concrete block as shown in Fig. 6.12b.

The specimens for the debonding detection analysis included three different sizes of concrete blocks, 250 mm x 250 mm x 250 mm concrete cube was used for investigation of lengthwise and widthwise debonding in the centre of the specimen. The cube with a dimension of 250 mm x 250 mm x 100 mm was used to investigate widthwise debonding in the side of the specimen, while 200 mm x 200 mm x 200 mm concrete cube was used to investigate patch debonding. With a 250 mm x 250 mm x 250 mm concrete cube, two different CFRP plates: 240 mm x 100 mm x 5 mm (referred to as concrete-CFRP 3) and 150 mm x 50 mm x 2 mm (referred to as concrete-CFRP 4) were used as shown in Fig. 6.17b-c. With a 250 mm x 250 mm x 100 mm cube, a CFRP plate with a dimension of 235 mm x 155 mm x 2 mm (referred to as concrete-CFRP 5) was used as shown in Fig. 6.27. Similarly, with a smaller concrete cube (with dimension 200 mm x 200 mm x 200 mm), two different CFRP plates: 150 mm x 50 mm x 2 mm (referred to as concrete-CFRP 6) and 190 mm x 100 mm x 5 mm (referred
to as concrete-CFRP 7) was used as shown in Fig. 6.31. These CFRP plates were bonded to the concrete cubes using an epoxy Sikadur-30.

Sikadur-30 is an adhesive mortar based on 2-component solvent free epoxy resin. It is used to bond structural reinforcements to other substrates. It is also used to bond and fill wide variety of building and construction materials. Sikadur-30 was mixed in the laboratory by combining the Part A (Resin) and Part B (Hardener) in the ratio of 3:1. Before mixing, these component were thoroughly stirred using a slow running stirrer. Then, Part B was decanted into Part A and mixed thoroughly until a uniform colour was achieved. Once a streaky colour was obtained, the epoxy was applied immediately to the cleaned and abraded concrete surface.

6.5.2 Detection of gap between early-age concrete and CFRP

Multiple measurements were taken with no gap (0 mm) and with gap values: 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm. Then, the average of these measurements vs time and standard deviation were calculated. Further, damage indexes including a correlation coefficient, peak-to-peak (P2P) amplitude and root-mean-square deviation (RMSD) were used for quantitative analysis of the gap. The measurements were conducted at 1, 2, 6, 24 and 48 hours after concrete casting to determine the gap at different stages of fresh and hardened concrete since gap may occur between CFRP composite and early-age of concrete due to shrinkage.

![Diagram](image)

**Figure 6.12:** Experimental setup for detection and monitoring of gap between CFRP plate and concrete using transducers: (a) schematic and (b) picture of the concrete-CFRP 1 with transducers after 72 hours (A – Actuator and S – sensor).
Fig. 6.13a-b shows the average voltage measurement vs time at no gap and 0.2-mm gap in specimens: concrete-CFRP 1 and 2, respectively, for 1-hour concrete. It can be seen from Fig. 6.13 that there is a difference between the average reference signal and average signals with gap which indicated the presence of gap for both specimens and this difference is larger for concrete-CFRP 2 than for concrete-CFRP 1. It can be attributed to the fact that the CFRP plate in concrete-CFRP 1 is thicker than the CFRP plate in concrete-CFRP 2 which leads to higher concentration of stress wave inside the thicker plate and lower sensitivity to the small change of CFRP plate-concrete interface. The maximum standard deviation of reference signal and signal at gap values of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were determined to be 0.35, 0.21, 0.33, 0.36 and 0.39, and 0.11, 0.09, 0.13, 0.12 and 0.11, for concrete-CFRP 1 and concrete-CFRP 2, respectively. The results show that the standard deviation in concrete-CFRP 2 is lower at each gap than concrete-CFRP 1. Again, it can be attributed to lower sensitivity of the proposed technique to the gap for thicker CFRP plate.

Figure 6.13: Average output voltage vs time in (a) concrete-CFRP 1 and (b) concrete-CFRP 2 for 1 hour-concrete at gap values: 0 mm and 0.2 mm.

The correlation coefficient [158] was determined between the average reference signal and average signal at each gap in both specimens to determine the similarity/difference between these signals. The correlation coefficient plot for 1-hour concrete in concrete-CFRP 1 and concrete-CFRP 2 is shown in (left) Fig. 6.14a-b, respectively. It can be seen from the plots that the correlation coefficient decreases with increasing gap value which shows that the dissimilarity between the reference signal and signal with gap
increased. Further, linear fitting was carried out. The coefficient of determination ($R^2$) for concrete-CFRP 1 was determined to be 0.99 and for concrete-CFRP 2 was determined to be 0.88 which imply that the corresponding gap can be predicted from this fitted curve. The second damage index was P2P amplitude. To get P2P amplitude, the resultant signal was obtained at each gap value by subtracting the average signal at different gap values against the average reference signal. The P2P amplitude of this resultant signal was plotted, and linear fitting was applied. The P2P amplitude plot for both specimens for 1-hour concrete is shown in (right) Fig. 6.14a-b, respectively. It can be clearly seen from these figures that the P2P amplitude increases with increasing gap. From linear fitting, $R^2$ was determined to be 0.95 in concrete-CFRP 1 and 0.81 in concrete-CFRP 2.

Figure 6.14: Correlation coefficient (left) and change in P2P voltage of the resultant signal (right) with fitted curves at different values of a gap for 1 hour-concrete in (a) concrete-CFRP 1 and (b) concrete-CFRP 2.

The correlation coefficient at each time interval was then compared to see the effect of duration of concrete casting on the gap detection. The correlation coefficient with linear fitting for 0.2 mm gap at a different time interval from 1 hour to 24 hours of concrete casting in concrete-CFRP 1 and 2 is shown in Fig. 6.15a-b, respectively. The
R² value for concrete-CFRP 1 and concrete-CFRP 2 were determined to be 0.98 and 0.95 respectively. The decrease in correlation coefficient with time indicates that the difference between the reference signal and damage signal is significant, once the fresh concrete starts to settle. The gap of 0.2 mm was used for demonstrative purpose while all the gaps showed a similar trend. This proves that the indication of a gap in the concrete based composite structure is more prominent as the time of concrete casting increase.

**Figure 6.15:** Change in correlation coefficient for 0.2 mm gap over time (hours) in (a) concrete-CFRP 1 and (b) concrete-CFRP 2.

Fig. 6.16 shows the RMSD at different gaps at a different time interval of concrete casting for concrete-CFRP 1 and concrete-CFRP 2. For concrete-CFRP 1 (c.f., Fig. 6.16a), the RMSD values increased from 0.14 to 0.19 for gap value ranging from 0.1 mm till 0.4 mm for 1-hour concrete. Similar trends were observed for 6-hours, 24-hours and 48-hours concrete. For 48-hours concrete, the RMSD value increased from 0.21 for 0.1 mm gap to 0.27 for 0.4 mm gap. For concrete-CFRP 2 (c.f. Fig. 6.16b), the RMSD values increased from 0.06 to 0.15 for gap value ranging from 0.1 mm till 0.4 mm for 1-hour concrete. In 48-hours concrete, RMSD values increased from 0.20 to 0.35 for gap value ranging from 0.1 mm till 0.4 mm. This shows that increasing gap provided larger RMSD value. These RMSD values can be correlated with the gap values and can be used as a gap value index. Further, it can be noted that as the time of concrete casting increased, the RMSD level also increased which proves that indication of a gap in the concrete based composite structure is more prominent as the time of concrete casting increased.
Figure 6.16: RMSD values at the different time of concrete casting at different values of a gap for (a) concrete-CFRP 1 and (b) concrete-CFRP 2.

The above results showed the feasibility of the detection and evaluation of the gap between CFRP plate and concrete using the proposed piezoelectric sensing system. Statistical analysis indicated a correlation coefficient and P2P amplitude vary with varying gap value. The high value of $R^2$ of the fitted curve implied that it could be used for measurement of gap value. The damage indexes also showed that the gap values could be correlated quantitatively with these indexes. The linear trend in change of correlation coefficient and RMSD values with time of concrete casting showed that gap indication is more prominent in settled concrete and implies its applicability in dry concrete as well.

6.5.3 Detection of debonding in concrete-CFRP structures

Multiple measurements were taken when the structure was intact (i.e. without debonding) and the average of these measurements was taken as a reference. Then, multiple measurements were taken when CFRP plate debonded from the concrete. Side debondings were created by scrapping out the epoxy layer from the sides of the composite structure while the debondings in the middle of the composite structure were created while applying the epoxy layer to the concrete. Multiple specimens were created with a variety of debonds such as lengthwise and widthwise debondings and patch debondings in the centre of the structure. The experimental setup for the measurement is shown in Fig. 6.17a.
Figure 6.17: Experimental method and specimens: (a) measurement setup, (b) concrete-CFRP 3 and (c) concrete-CFRP 4.

6.5.3.1 Lengthwise debonding in the centre of the specimen

In this study, 1.4 mm deep and 1 mm wide debond was created with varying length. First, 20 mm debond was made during the application of epoxy, and the CFRP plates were placed in the position till the epoxy hardened. Piezoelectric transducers were attached to the external surface of the CFRP plates at a distance of 50 mm between them. A sine burst signal with 5 peaks were generated by an actuator (A) and received by a sensor (S). Similar procedures were followed for debonding of lengths 40 mm, 60 mm, 80 mm and 100 mm. The measurements were performed for concrete-CFRP 3 and concrete-CFRP 4 specimen and the schematic of the experimental setup and the position of CFRP plates with respect to the debonds is shown in Fig. 6.18.
Figure 6.18: Schematic of experimental setup showing the position of CFRP plates on the concrete block with lengthwise debonding.

The maximum standard deviation of the reference signal and the signal at debondings with length 20 mm, 40 mm, 60 mm, 80 mm and 100 mm in concrete-CFRP 3 were determined to be 0.005, 0.008, 0.002, 0.004 and 0.004, respectively. Similarly, for concrete-CFRP 4, the standard deviation of the reference signal and the signal at debondings with length 20 mm, 40 mm, 60 mm, 80 mm and 100 mm were determined to be 0.018, 0.013, 0.007, 0.017, 0.011 and 0.019, respectively. The low values of standard deviation show the good repeatability rate of the measurement. Next, the correlation coefficient was determined between the average reference signal and the average signal at each debonding for both specimens. The higher correlation coefficient value means more correlation between the signal and hence less damage. Therefore, “1-cc (correlation coefficient)” is used instead of correlation coefficient to determine the increase in damage index by increasing the severity of damage. The “1-cc” plot for increasing debonding length in concrete-CFRP 3 and concrete-CFRP 4 is shown in Fig. 6.19a and 6.19b, respectively. It can be seen from the plots that the “1-cc” index increased with increasing debonding length which shows that the
dissimilarity between the reference signal and signal with debonding increased. Further, linear fitting was carried out. The coefficient of determination ($R^2$) for concrete-CFRP 3 was determined to be 0.93, and for concrete-CFRP 4 was determined to be 0.91 which imply that the further debonding could be predicted from this fitted curve.

![Figure 6.19](image)

**Figure 6.19:** $1 - \text{CC}$ correlation coefficient with fitted curves at different debonding length in (a) concrete-CFRP 3 and (b) concrete-CFRP 4.

Similar to the previous measurements, the second damage index was P2P amplitude. To get P2P amplitude, the resultant signal was obtained at each lengthwise debonding by subtracting the average signal at these debonds against the average reference signal. The P2P amplitude of this resultant signal was plotted, and linear fitting was applied. The P2P amplitude plot for both specimens is shown in Fig. 6.20a-b, respectively. Similar to the previous index, the P2P amplitude increased with the increasing gap. From linear fitting, $R^2$ was determined to be 0.91 in concrete-CFRP 3 and 0.96 in concrete-CFRP 4.
Figure 6.20: Change in P2P voltage of the resultant signal with fitted curves at different debonding length in (a) concrete-CFRP 3 and (b) concrete-CFRP 4.

Fig. 6.21a-b shows the RMSD at different debond lengths for concrete-CFRP 3 and concrete-CFRP 4, respectively. For concrete-CFRP 3 (c.f., Fig. 6.21a), the RMSD values increased from 0.32 to 0.49 for debond length ranging from 20 mm till 100 mm. For concrete-CFRP 4 (c.f. Fig. 6.21b), the RMSD values increased from 0.11 to 0.49 for debond length ranging from 20 mm till 100 mm. This shows that increasing debonding length increased the RMSD value. The RMSD values accurately correlated with the increase in damage (i.e. the length of debonding).

Figure 6.21: RMSD at different debonding length in (a) concrete-CFRP 3 and (b) concrete-CFRP 4.
6.5.3.2 Widthwise debonding in the centre of the specimen

In this study, 1.4 mm deep and 100 mm long debond was investigated with varying width. The debond of width 2 mm, 4 mm, 6 mm and 8 mm were introduced to the structure near the centre. Piezoelectric transducers were attached to the external surface of the CFRP plates at a distance of 50 mm between them. A sine burst signal with 5 peaks were generated by an actuator (A) and received by a sensor (S). The measurements were performed for concrete-CFRP 3 and concrete-CFRP 4 specimen and the schematic of the experimental setup and the position of CFRP plates with respect to the debonds is shown in Fig. 6.22.

![Figure 6.22: Schematic of experimental setup showing the position of CFRP plates on the concrete block and widthwise debonding.](image)

The maximum standard deviation of the reference signal and the signal at debondings with width 2 mm, 4 mm, 6 mm and 8 mm in concrete-CFRP 3 were determined to be 0.005, 0.018, 0.010, 0.006 and 0.076, respectively. Similarly, for concrete-CFRP 4, the standard deviation of the reference signal and the signal at debondings with length 2 mm, 4 mm, 6mm and 8 mm were determined to be 0.018, 0.019, 0.013, 0.018 and
0.027, respectively. Next, the correlation coefficient was determined between the average reference signal and the average signal at each debonding width for both specimens and “1-cc” index was plotted. The “1-cc” plot for increasing debonding width in concrete-CFRP 3 and concrete-CFRP 4 is shown in Fig. 6.23a and 6.23b, respectively. “1-cc” index increased with increasing debonding width in both specimens. Linear fitting was carried out, and the coefficient of determination ($R^2$) for concrete-CFRP 3 was determined to be 0.98, and for concrete-CFRP 4 was determined to be 0.98 which were very high.

![Figure 6.23](image_url)

**Figure 6.23:** 1 - correlation coefficient with fitted curves at different debonding width in (a) concrete-CFRP 3 and (b) concrete-CFRP 4.

Next, the P2P amplitude of the resultant signal was plotted, and linear fitting was applied. The P2P amplitude plot for both specimens is shown in Fig. 6.24a-b, respectively. The P2P amplitude increased with the increasing gap. From linear fitting, $R^2$ was determined to be 0.83 in concrete-CFRP 3 and 0.93 in concrete-CFRP 4. The low $R^2$ value in concrete-CFRP 3 is mainly because of the atypical value obtained for 8 mm width debonding which can be attributed to measurement error which is also highlighted by higher standard deviation value compared to other debonding measurements.
The RMSD at different debond widths for concrete-CFRP 3, and concrete-CFRP 4 were plotted as shown in Fig. 6.25a-b, respectively. The RMSD values increased from 0.78 to 1.54 for debond width ranging from 2 mm till 8 mm in concrete-CFRP 4. The measurement error described previously is the reason for irregularly large RMSD value at 8 mm width. Similarly, the RMSD values increased from 0.58 to 1.33 for debond width ranging from 2 mm to 8 mm. The RMSD values accurately correlated with the increase in damage (i.e. the width of debonding) in this case as well.
change in P2P and RMSD). This indicated that as the size of debonding increased, the sensitivity of detecting the debonding also increased. The debonding of size as small as 10 mm x 1 mm x 1.4 mm were detected accurately.

6.5.3.3 Widthwise debonding in the side of the specimen

The lengthwise and widthwise debonding were successfully detected in the previous section. However, the debondings were produced in the centre of the specimen and the debonding region was situated between the actuator and sensor. This way, the debonding directly obstructed the path of the generated sine burst signal from the actuator to sensor resulting in accurate detection. However, in a real-life scenario, the origin of debonding would be unknown, and there is a need to detect debondings even when they originate in different locations far away from the piezoelectric transducers. For this reason, measurements with widthwise debonds were performed on the side of the specimen for concrete-CFRP 5. Piezoelectric transducers were attached to the external surface of the CFRP plates at a distance of 50 mm between them. A sine burst signal with 5 peaks were generated by an actuator (A) and received by a sensor (S). The schematic of the experimental setup and the position of CFRP plates with respect to the debonds is shown in Fig. 6.26.
A reference data was taken at perfect bonding, and different debonding condition was obtained at the left end of the CFRP and concrete bond (cf. Fig. 6.27). This debonding was created using an electric cutter. The cut with a depth of 2 mm, length of 235 mm and three widths – 10 mm, 20 mm and 30 mm were made to simulate three different debonding conditions.
Figure 6.27: Picture of the sample and experimental setup for lengthwise side debonding: (a) top view and (b) side view.

The maximum standard deviation of the reference signal and the signal at debondings with width 10 mm, 20 mm and 30 mm in concrete-CFRP 5 were determined to be 0.019, 0.007, 0.011 and 0.006, respectively. The “1-cc” index was plotted for different debonding widths as shown in Fig. 6.28a. Similarly, another index “change in P2P” was plotted for different debonding widths as shown in Fig. 6.28b. Further, linear fitting was carried out. The coefficient of determination ($R^2$) for the fitted curve of the “1-cc” index was determined to be 0.97 and of “change in P2P” index was determined to be 0.99. These high $R^2$ values show that these indexes are changing linearly with changing debonding value and thus could be used to predict the extent of debonding.
Figure 6.28: Statistical indexes with fitted curves at different debonding width: (a) $R^2 = 0.97$ – correlation coefficient and (b) change in P2P voltage of the resultant signal.

The next damage index, RMSD at different debond widths for concrete-CFRP 5 was plotted as shown in Fig. 6.29. The RMSD values for debonding widths 10 mm, 20 mm and 30 mm were determined to be 0.253, 0.450 and 0.640, respectively. As expected, RMSD values were increasing linearly with increasing debond size.

Figure 6.29: RMSD at different debonding width.

6.5.3.4 Patch debonding in the centre of the specimen
After accurate detection of lengthwise and widthwise debonding, different patch debondings were investigated in the centre of the specimen. First, three different circular debonding patches with diameter 15 mm, 25 mm and 35 mm were made. These patches were used to simulate debonding without sharp edges. Next, three
different square debonding patches with sides 17 mm, 28 mm and 37 mm were made. These patches were used to simulate debonding with sharp edges. The schematic of experimental setup with the position of CFRPs on the concrete and debond location is shown in Fig. 6.30. Piezoelectric transducers were attached to the external surface of the CFRP plates at a distance of 50 mm between them. A sine burst signal with 5 peaks were generated by an actuator (A) and received by a sensor (S). Two different specimens concrete-CFRP 6 and concrete-CFRP 7 were used for this investigation.

Figure 6.30: Schematic of the experimental setup showing the position of CFRP plates on the concrete block and patch debonding.

Multiple measurements were taken with a perfectly bonded structure and with different sized circular and square patches. The average values of these measurements were analysed for debond detection. For concrete-CFRP 6, the maximum standard deviation of the reference signal and circular patch debond of diameter 14 mm, 25 mm and 35 mm were determined to be 0.060, 0.088, 0.108 and 0.035, respectively. Similarly, the maximum standard deviation of the reference signal and square patch debond with sides 17 mm, 28 mm and 37 mm were determined to be 0.060, 0.168, 0.031 and 0.034, respectively. For concrete-CFRP 7, the maximum standard deviation of the reference signal and circular patch debond of diameter 14 mm, 25 mm and 35 mm were
determined to be 0.025, 0.004, 0.013 and 0.035, respectively. Similarly, the maximum standard deviation of the reference signal and square patch debond with sides 17 mm, 28 mm and 37 mm were determined to be 0.025, 0.008, 0.008 and 0.036, respectively.

![Figure 6.31: Picture of experimental setup: (a) with concrete-CFRP 6 and (b) with concrete-CFRP 7.](image)

Fig. 6.32 shows “1 – cc” index for different circular and square patch debondings with increasing debonding values. There was a clear indication of a change in damage index with increasing damage severity. Further, square debondings showed greater change in the indexes compared to circular debondings on both these specimens. This is mainly due to the sharp edges of square debondings due to which there was a significant change in the reflected signal compared to the reference signal. Also, the change in the signal between square and circular debondings are higher in concrete-CFRP 6 (cf. Fig. 6.32a) compared to concrete-CFRP 7 (cf. Fig. 6.32b). This might be due to the thinner CFRP plate used in concrete-CFRP 6 which led to higher sensitivity. Next, change in P2P voltage was plotted with respect to change in debonding values of circular and square patches as shown in Fig. 6.33. Similar observations were made with the index increasing with increasing damage severity.
Figure 6.32: 1 - Correlation coefficient at different patch debondings in (a) concrete-CFRP 6 and (b) concrete-CFRP 7.

Figure 6.33: Change in P2P voltage of the resultant signal at different patch debondings in (a) concrete-CFRP 6 and (b) concrete-CFRP 7.

The next damage index, RMSD at different circular and square patch debonds for concrete-CFRP 6 and 7 were plotted as shown in Fig. 6.34a and Fig. 6.34b, respectively. The RMSD values for circular debondings in concrete-CFRP 6 with diameter 14 mm, 25 mm and 35 mm were determined to be 0.475, 0.632 and 0.750, respectively. Similarly, the RMSD values for square debondings with sides 17 mm, 28 mm and 37 mm were determined to be 0.775, 0.846 and 1.116, respectively. In concrete-CFRP 7, the RMSD values for circular debondings with diameter of 14 mm, 25 mm and 35 mm were determined to be 0.472, 0.488 and 0.520 respectively.
Similarly, for square debondings with sides 17 mm, 28 mm and 37 mm, the RMSD values were determined to be 0.479, 0.494 and 0.537, respectively. As the other damages indices suggested, RMSD values also increased with increasing debond size. Further, the sensitivity of damage detection in concrete-CFRP 6 with thinner CFRP plate was higher than in concrete-CFRP 7 with thicker CFRP plate.

![Graph showing RMSD values at different patch debondings](image)

**Figure 6.34:** RMSD values at different patch debondings in (a) concrete-CFRP 6 and (b) concrete-CFRP 7.

The above results show that the size of debonding increased all three damage indexes and the change in the values of these damage indexes correlated with the extent of damages. This shows that the proposed technique is also able to detect patch debonding besides the lengthwise and widthwise debonding described in the previous section.

### 6.5 Summary

A piezoelectric sensor technique for the detection of the gap between metal and concrete in metal-concrete composite structures, the gap between CFRP and early-age concrete surfaces and debonding between CFRP and concrete is proposed. The results showed that the proposed technique is relatively simple, one-sided, non-invasive and cost-effective solution to detect gaps and debondings between conductive materials like metals/CFRPs and concrete in composite structures such as concrete-filled steel tubes, concrete-filled FRP tubes and CFRP reinforced concrete structures. Statistical indexes including correlation coefficient, the P2P amplitude of resultant signal and RMSD showed good correlation with the extent of the damage.
Overall, the proposed technique is (1) fully non-invasive technique as both actuators and sensors are only attached to the external surface of the specimen, (2) able to detect the gaps and debondings between thick metal and CFRP plate (≥ 5 mm) and concrete and (3) able to detect very small gaps and debondings (~ 0.1 mm). The detection of such small gaps and debonds is important for early retrofitting of structures preventing further damage and failure. The developed technique is applicable in real life structures with different static and dynamic loadings as well as with different ambient conditional changes such as vibrations. This is due to the fact the technique is a reference based damage detection technique where the subtracted signal between damage and reference signals are used. In this case, even if any unwanted effects such as noise or vibration is present, it will be observed in both the reference and damage signal and will be negated during the calculation of damage indices. Thus, the proposed technique can be used for detection of gaps, debondings as well as bond slips in a variety of composite materials.
Chapter 7 Conclusions and Recommendations

7.1 Summary
Civil infrastructures are composed of a variety of construction materials with varying electrical, chemical, mechanical and geometrical properties. These materials mainly include concrete, metals, alloys, polymers and fibre composites. The detection of flaws in these diverse materials is always a challenging task. Several NDT methods are being used to investigate flaws in these materials which give early warning of the degradation of the structure. These NDT methods are mostly applicable to materials with specific properties. For example, ultrasonic techniques are mostly capable of detecting flaws in conducting materials like metals. However, a single NDT method is not able to investigate a variety of materials. Among these methods, microwave near-field NDT technique has been relatively successful in detecting flaws in a variety of dielectric and conducting materials. The major drawback of this technique is the change in standoff distance which limits the application in structures with different geometrical shapes.

In this thesis, a novel dual laser integrated microwave imaging system is developed to overcome the limitation of existing microwave near-field NDT technique which is capable of detecting flaws in specimens of different geometric shapes and curvatures with automatic adjustment of the standoff distance. The developed system utilises two laser displacement sensors which give feedback to the scanning unit on the distance of the microwave antenna from the structure which enables the automatic optimisation of standoff distance for complex geometric shaped structures. During the process of development of this integrated imaging system, two independent NDT system – laser displacement profiling and imaging system, and microwave imaging system were also developed. Further to highlight the importance of an integrated approach to NDT for a variety of construction materials, a methodology for interfacial defect detection in composite material using piezoelectric sensing technique is developed. The development of different standalone and integrated system highlighted the need for synergy between different NDT techniques.
The major investigations and research findings in each chapter of this thesis can be summarised as follows:

In **chapter 3**, a novel laser profiling and imaging system were developed using a single LDS attached to the scanner. The profiling and imaging system was capable of investigating structures with complex surface profiles for the purpose of detection and evaluation of surface flaws such as cracks and impact damages. In 1-D profiling, a characteristics response of crack was obtained as a sharp distortion of the displacement reading when the laser spot crossed the crack. Further, RMSD was used to quantify the extent of crack. RMSD value accurately correlated with the width of the crack. The direction of a scan on crack detection was investigated, and the results showed that although the characteristic response of crack changed, it did not show a significant impact on crack detection. In 2-D and 3-D imaging, the reading of displacement from the sensor head to the laser spot on the surface of the test materials was used to generate images which visualised the surface flaws. The effect of changes of distance inside the cuts/cracks and the effect of tilt angle and surface roughness were investigated, and the results showed these effects have a negligible effect on crack/cut detection. However, rougher surface gave more accurate displacement measurement and hence more accurate crack/cut detection. The advantage of the developed system was the non-contact nature and the ability of the system for profiling and surface flaw detection in variety of infrastructure materials with different dielectric, chemical and geometrical properties.

In **chapter 4**, the microwave imaging system was developed for defect detection in planar construction materials and structures. The developed system was used to detect hidden and surface flaws in a variety of materials including metals, dielectric materials, composite materials and cement based specimens. The magnitude and phase of reflection coefficient were used to plot microwave images in planar and tilted specimens. For tilted specimens, the standoff distance was adjusted manually by controlling the movement of Z-axis based on tilt angle and scan area. Two different polarizations, perpendicular and parallel polarization were used with respect to the defect (notch), and the results showed that the raw images using perpendicular polarization gave clearer indication of the notch. Several targets hidden inside layers
were detected successfully. Further, defects like cracks, holes and gaps were detected in both exposed and covered specimens. Next, a proof-of-concept was provided for wireless microwave sensing system where a wireless data acquisition system was successfully applied for determining the microwave properties of the material.

In chapter 5, a novel dual laser integrated microwave imaging system was developed. The developed system consisted of a novel integrated sensing unit with two laser displacement sensors and a single microwave antenna that automatically followed the contour of the material under test at a constant standoff distance and generated microwave images. The system performed contour following at the hardware level and did not require any calibration or complex compensation algorithm. The comparison of two microwave antennas – OEWA and DA were performed to find a suitable antenna for different materials. The proof of concept of the developed system for the non-destructive testing of construction materials with different geometrical shapes was provided. The crack with a width of ~ 1 mm was detected. The developed system overcomes the limitation of current microwave imaging system for investigation and analysis of a wide range of construction materials and structures. Further, the system is robust and gives real-time information of any flaws on the structure without the need for complex image processing.

In chapter 6, a methodology for interfacial defects in concrete based composite structures using piezoelectric sensing technique was presented. The measurement technique was utilised for gap detection between metal/concrete and CFRP/concrete, and debonding detection between CFRP and concrete. The developed technique used propagation properties of the guided waves in the metal and CFRP plate excited and received by piezoelectric based transducers attached to the external surface. A gap of 0.1 mm was detected between metal and concrete as well as between CFRP and concrete. Similarly, debondings as small as 1 mm width was detected between CFRP and concrete. Besides, all three damage indexes: correlation coefficient, change in P2P value and RMSD showed good correlation with the severity of damage.
7.2 Conclusion

The non-destructive testing of construction materials and structures with microwave, laser and piezoelectric sensing techniques were performed. Based on the different properties of materials under test, these techniques were applied either separately or simultaneously for their investigation. Further, a novel imaging sensor system for NDT was developed by integrating microwave and laser sensor techniques to utilise the benefit of these techniques and their combination for NDT applications in demand. The developed systems were utilised in a variety of materials for the purpose of detection of a variety of flaws. The diagnosis of these flaws at the preliminary stage is vital for safety and reliability of structures that directly impact people’s life. The developed systems were tested successfully in a laboratory environment for the proof of concept. The application of these systems in the real-world scenario is an important issue because the ambient condition might lead to different uncertainties which might affect the measurement parameters. The detailed investigation of the real world application of the developed systems is recommended for future studies. This investigation will enable the optimisation of the developed system. For example, determining the optimal frequency of the microwave signal to interrogate concrete bridges, determining the optimal step size in a laser imaging system for an online investigation of machine parts.

The summary of the application area of the developed system is given in Table 7.1. The table shows that the developed systems in this thesis are capable of detecting principal flaws that are preliminary indications of structural failure. However, the potential area of application of these systems is not limited to these flaws and materials. The developed systems could be optimised and applied in diverse areas as the primary aim of this study is to solve practical NDT problems through the integration of multiple NDT systems. This integrated approach can provide reliable information on the state of health of the structures preventing catastrophic failure.
Table 7.1: Summary of the application of the developed system in diverse construction materials and flaws.

<table>
<thead>
<tr>
<th>System developed</th>
<th>Materials used</th>
<th>Flaws detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser imaging system</td>
<td>Metal</td>
<td>Cuts, through-cuts</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>Cracks, through-cracks, blowholes</td>
</tr>
<tr>
<td></td>
<td>Polymer</td>
<td>Cracks</td>
</tr>
<tr>
<td>Microwave imaging system</td>
<td>Metal</td>
<td>Embedded targets, Exposed and hidden holes and through-gaps</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>Exposed and hidden notches and through-cracks</td>
</tr>
<tr>
<td></td>
<td>Polymer</td>
<td>Embedded targets</td>
</tr>
<tr>
<td>Dual laser integrated microwave imaging system</td>
<td>Metal</td>
<td>Exposed and hidden cracks and through-cracks</td>
</tr>
<tr>
<td></td>
<td>Polymer</td>
<td>Targets</td>
</tr>
<tr>
<td>Piezoelectric system</td>
<td>Metal/concrete</td>
<td>Gaps</td>
</tr>
<tr>
<td></td>
<td>CFRP/concrete</td>
<td>Gaps, debondings</td>
</tr>
</tbody>
</table>

7.3 Recommendations for future research

Based on the research findings and preliminary results from the developed system and methodology, suggested future work is summarised as follows:

1. **Wireless microwave imaging system**: Preliminary results and proof-of-concept of the wireless microwave sensing system is given in chapter 4. These results prove the applicability of the wireless data acquisition device to replace bulky data acquisition devices currently being used for microwave sensing.
However, for all the proposed microwave imaging techniques, PNA was used for microwave signal generation which is a bulky and expensive device with the addition of cables and connectors associated with the device. On the other hand, it was shown in the thesis that only magnitude and phase of reflection coefficient can be used for desired measurements and imaging. It means that a relatively simple signal generation and measurement unit as a transceiver can be used. Several portable reflectometers are present today which can be used for this purpose to realise a complete wireless microwave imaging system.

2. **Field performance of dual laser integrated microwave imaging system:**

Upon the excellent performance of the dual laser integrated microwave imaging system in a laboratory environment, it would be of interest to know how the technique performs on real structures in field conditions. Not only the background electromagnetic noises could be present, but also the operational constraints in the field could lead to the need for further optimisation of the technique. With proper optimisation, the developed system could be integrated with different scanning mechanisms and could be used in the diverse field in civil, mechanical and aerospace sector. For instance, use of the developed system with robotic arms in the manufacturing industry for real-time process monitoring.

3. **Piezoelectric imaging system for debond detection:** Piezoelectric sensing system was successfully used for debonding and gap detection in composite structures mainly concrete-CFRP structure and concrete-metal structure in chapter 6. The developed methodology utilised a single actuator and a sensor for defect detection as the main purpose was to develop a simple and robust flaw detection technique. However, multiple actuator and sensor combinations could be used to localise the position of flaws. Further, the use of different algorithms such as using total signal energies of reference and damage signal could be used to generate images to visualise these flaws.
References


Y. J. Kim, L. Jofre, F. De Flaviis, and M. Q. Feng, "Microwave subsurface imaging technology for damage detection," *Journal of engineering mechanics*, vol. 130, no. 7, pp. 858-866, 2004.


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