

**Structural Health Monitoring of concrete structures by
integrating Infrared Thermography with compatible Non-
Destructive Tests to quantify and characterize defects**

A Thesis submitted in partial fulfilment for the Degree of

DOCTOR OF PHILOSOPHY

in Civil Engineering
Faculty of Engineering
GOA UNIVERSITY



By

Madhuraj Kiran Naik

GOA COLLEGE OF ENGINEERING, FARMAGUDI

GOA UNIVERSITY

JUNE 2025

DECLARATION

I, Madhuraj Kiran Naik hereby declare that this thesis represents work which has been carried out by me and that it has not been submitted, either in part or full, to any other University or Institution for the award of any research degree.

Place: Taleigao Plateau.

Date: 24-06-2025

Madhuraj Kiran Naik

CERTIFICATE

I hereby certify that the above Declaration of the candidate, Madhuraj Kiran Naik is true and the work was carried out under my supervision.

Dr. Ganesh Hegde

Professor

Civil Engineering Department

Goa College of Engineering, Farmagudi

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my sincere thanks and gratitude towards my supervisor, Dr. Ganesh Hegde, for his continuous guidance, encouragement and strong support during the course of my Ph.D. research. I am eternally grateful for his kindness, helpful guidance, discussions, and dazzling sense of humor.

I express my sincere gratitude towards Dr. M.S. Krupashankara, Principal, Goa College of Engineering for granting me permission to continue my PhD and guiding me throughout my PhD journey. I am thankful to Dr. AKS Bhadauria, Head, Civil Engineering Department for his guidance and support. I am also thankful to Dr. K.G. Guptha, Professor (Retired), Department of Civil Engineering for his guidance and support. I am eternally grateful to Dr. Lalat Indu Giri, NIT Goa for his valuable and timely guidance on infrared thermography and subsequently training me on using infrared camera for my experiments. I am grateful to Dr. Govind Kunkolienkar, Head of Electrical Engineering Department for providing me with his valuable insight and also allowing me to use equipment in electrical department laboratories. I thank my DRC committee members Dr. Neena Panandikar, Principal, Don Bosco College of Engineering for all the support and valuable advice she has given to me and Dr. Jennifer Lewis, who provided useful suggestions and valuable advice during my research work. I am grateful to Er. Kaizad and his technical team for being kind enough to lend me equipment for Ultrasonic Pulse Echo (UPE) test which was very important part of my research.

I express my special thanks to all the lab assistants of civil engineering and electrical engineering department, Goa College of Engineering who provided support during my experimental work. I also express my gratitude towards faculty members of civil department and all my colleagues at the Goa College of Engineering, Farmagudi who directly or indirectly contributed towards my research.

Special thanks goes to my wife and my parents for their encouragement and sacrifices. Their support and motivation gave me the foundation to thrive and succeed.

ABSTRACT

It is necessary to conduct timely testing and maintenance of concrete structures to check for defects as they reduce strength and integrity. Several Non-destructive Testing (NDT) methods like rebound hammer, ultrasonic pulse velocity are currently adopted for structural audit and evaluation. These methods require access to the surface of object which is not always available. The thesis presents research on infrared thermography as Non-destructive Testing (NDT) method for concrete primarily focusing on sub-surface defects. It is a non-contact technique which involves scanning of surface with thermal camera to capture thermal images (thermograms) of the surface. The techniques like stepped, pulsed thermography and lock-in thermography are explored in the current study. A technique is developed to obtain area of sub-surface defects in concrete structures using thermograms. Further, the research is focused on direct and indirect methods to obtain depth of sub-surface defects in concrete. The study also explores methods to eliminate noise in thermal images and to identify deeper defects. A comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) method is also presented in this thesis.

The research commenced with an extensive literature survey and it was found that most of the research focused on identifying and locating the damages. The interpretation of the depth of defect and its area is largely left upto the user operating the camera. The results such as area and depth of defect are essential from a repair point of view and need to be determined accurately. Hence thermal images captured by an infrared camera require further processing using advanced image processing techniques that are utilized in this study.

In this study, a computer program-oriented algorithm is developed to calculate defect area. The program utilizes surface temperature values and calibration to determine area of sub-surface defects. An FEA simulation of the experiment has been conducted to tide over any unforeseen inconsistencies in the results. A separate parametric study was conducted using a different FEA simulation incorporating realistic conditions present during the experimental study. The critical parameters that affect defect area identification were identified in this study.

To calculate defect depth, both direct and indirect methods have been developed. The indirect method involves pseudo experiment of thermal imaging to be conducted on a concrete surface using FEA simulations. Lock in Thermography is performed on the FEA simulations and thermal images are obtained. The temperature contour on vertical sections passing through the defects is used to determine the depth of damage. The direct method involves the development of a modified depth calculation model based on thermal contrast principles, extending from

the work of Huh et al. (2018), which was developed and validated for concrete specimens. Pulsed Infrared Thermography was adopted for this method.

Various post processing methods were applied on the recorded thermal images i.e. Principal Component Thermography (PCT), Fourier Transform (Phase and Amplitude), Multiscale Retinex, Differential Absolute Contrast, Wavelet Transform and Markov Error Contrast. It is observed that defects at depth of 5 cm and more were visible when thermal images were processed using the Fourier Transform method. The Signal to Noise Ratio (SNR) is used to assess the detectability of defects.

The increased duration of thermal excitation improves defect area detection, particularly in stepped thermography, while defect depth estimation remains unaffected by excitation intensity or duration in lock-in thermography. In the present study, equations for depth estimation were developed that exhibited improved accuracy compared to existing models, with an error margin below 2% for defects up to 10 cm deep and with a width-to-depth ratio of 2 or greater. Furthermore, IRT proved superior to the Ultrasonic Pulse Echo (UPE) method in terms of speed and spatial resolution for defect characterization. The research concludes that integrating active IRT with refined image processing and defect quantification techniques developed in this study significantly enhances the efficiency and reliability of SHM in concrete structures.

Table of Contents:

Chapter 1	1
Introduction.....	1
1.1 General	1
1.1.1 Stefan’s law of radiation	5
1.1.2 Wien’s displacement law	5
1.1.3 Infrared (IR) camera	5
1.2 Types of Active Infrared Thermography	6
1.2.1 Stepped Thermography	6
1.2.2 Pulsed Thermography	7
1.2.3 Pulsed-Phased Thermography	8
1.2.4 Lock-in Thermography	8
1.3 Numerical simulation	9
1.4 Motivation and objective of thesis	10
Chapter 2.....	13
Literature Review.....	13
2.1 Introduction	13
2.2 Literature summary	13
Chapter 3.....	21
Method to calculate defect area in concrete from thermal images	21
3.1 Outline of study	21
3.2 Objectives and scope.....	22
3.3 Methodology	23
3.3.1 Casting of concrete slab	23
3.3.2 Active infrared thermography on slab	25
3.3.3 Thermal image processing using computer program.....	26
3.3.4 FEA simulation of experiment.....	29
3.3.5 Parametric study using FEA simulation	32
3.4 Results	34
3.4.1 Active infrared thermography experiment.....	34
3.4.2 FEA simulation of active infrared thermography experiment	36
3.4.3 Parametric study.....	39
3.5 Observations.....	43
Chapter 4.....	45
FE simulation technique (Indirect method) to obtain defect depth.....	45

4.1	Outline of study.....	45
4.2	Objectives and scope.....	45
4.3	Methodology	47
4.3.1	FEA simulation.....	47
4.3.2	FE simulation of Lock-in Thermography	49
4.4	Results.....	52
4.5	Observations.....	62
Chapter 5.....		63
Direct method to calculate defect depth based on thermal contrast		63
5.1	Outline of study.....	63
5.2	Objectives and scope.....	64
5.3	Experimental study	65
5.3.1	Casting of concrete Slab	65
5.3.2	Experimental setup	68
5.4	Pulsed thermography experiment.....	69
5.5	Results and Discussions.....	72
5.5.1	Ten-minute heating regime.....	72
5.5.2	Twenty-minute heating regime.....	75
5.5.3	FEA simulation to obtain thermal diffusivity.....	78
5.5.4	Equation to predict depth.....	81
5.6	Application of depth equation.....	85
5.6.1	FEA model development	86
5.6.2	FEA analysis.....	86
5.7	Observations.....	89
Chapter 6.....		91
Technique to identify deeper defects in concrete using post processing method.....		91
6.1	Outline of study.....	91
6.2	Objectives and scope.....	91
6.3	Post Processing Methodology	92
6.4	Multiscale Retinex	94
6.5	Differential Absolute Contrast (DAC).....	96
6.6	Markov Error Contrast.....	99
6.7	Fourier Transform	101
6.8	Wavelet Transform	106
6.9	Principle Component Thermography	109

6.10	Spatial Noise Reduction	111
6.11	Histogram Equalization	112
6.12	Signal to Noise Ratio	112
6.13	Observations	115
Chapter 7		117
Comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) (Experimental verification)		117
7.1	Outline of study	117
7.2	Objectives and Scope	118
7.3	Experimental setup	118
7.4	UPE scan	120
7.5	Results	122
7.6	Observations	128
Chapter 8		131
Results and Discussions		131
8.1	Introduction	131
8.2	Method to calculate defect area in concrete from thermal images	131
8.3	FE simulation technique (Indirect method) to obtain defect depth	132
8.4	Direct method to calculate defect depth based on thermal contrast	133
8.5	Technique to identify deeper defects in concrete using post processing methods	135
8.6	Comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) (Experimental verification)	135
Chapter 9		137
Conclusions and future scope		137
9.1	Conclusions	137
Chapter 10		139
References		139
Conference Papers:		145
Journal Papers:		146
Annexure A		147
Program to calculate area of damage		147
Annexure B		157
Program to calculate Signal to Noise Ratio (SNR)		157

List of Figures:

FIGURE 1 TYPICAL THERMAL NON-DESTRUCTIVE TESTING (TNDT) SETUP	3
FIGURE 2 INTENSITY V/S WAVELENGTH PLOT FOR A HOT BODY AT DIFFERENT TEMPERATURES (WIENS DISPLACEMENT LAW) (SOURCE: S. GABRIEL PFAFFMAN)	5
FIGURE 3 TYPICAL COLOURED THERMOGRAM OF A RCC SLAB CAPTURED USING FLIR E6 HAND- HELD INFRARED CAMERA.....	6
FIGURE 4 PLOT OF TEMPERATURE V/S TIME FOR A SURFACE AFTER APPLICATION OF HEAT PULSE	7
FIGURE 5 PULSED EXCITATION	8
FIGURE 6 A) INCREASING TREND OF PLOT REPRESENTS DC COMPONENT WHILE WAVY PATTERN REPRESENTS AC COMPONENT B) PHASE IMAGE AND AMPLITUDE IMAGE.....	9
FIGURE 7 A FLOWCHART OF METHODOLOGY TO CALCULATE DEFECT AREA IN CONCRETE FROM THERMAL IMAGES	21
FIGURE 8 PLACEMENT OF DEFECT D1	23
FIGURE 9 A) PLACEMENT OF REBARS AND DEFECT D1 B) SLAB S1 AFTER CONCRETING	24
FIGURE 10 A) EXPERIMENTAL SETUP B) TYPICAL THERMAL IMAGE	25
FIGURE 11 A4 PAGE WITH DIFFERENT AREAS FOR TESTING OF ALGORITHM TO CALCULATE DEFECT AREA.....	27
FIGURE 12 SPATIAL CALIBRATION OF IMAGE USING PROGRAM	28
FIGURE 13 SPATIAL CALIBRATION OF IMAGE USING PROGRAM	28
FIGURE 14 SPATIAL CALIBRATION OF IMAGE USING PROGRAM	28
FIGURE 15 CALCULATED AREA OF DEFECT IS DISPLAYED	29
FIGURE 16 A) FEA MODEL OF SLAB USING ANSYS WORKBENCH B) TYPICAL THERMAL IMAGE OF SLAB	30
FIGURE 17 VARIATION OF THERMAL CONDUCTIVITY OF CONCRETE WITH TEMPERATURE.....	31
FIGURE 18 FEM MODEL OF SLAB AND HEATING SOURCE IN COMSOL	33
FIGURE 19 THERMAL IMAGES RECORDED AFTER A) 5 MINUTES B) 20 MINUTES C) 30 MINUTES D) 60 MINUTES DURING THERMAL EXCITATION	35
FIGURE 20 THERMAL IMAGES OBTAINED FROM FEA SIMULATION RECORDED AT DIFFERENT TIMES DURING THERMAL EXCITATION.....	38
FIGURE 21 PLOT SHOWING VARIATION OF DEFECT AREA OBTAINED USING 500 W SOURCE	40
FIGURE 22 PLOT SHOWING VARIATION OF DEFECT AREA OBTAINED USING 1000 W SOURCE	41
FIGURE 23 PLOT SHOWING VARIATION OF DEFECT AREA OBTAINED USING 2000 W SOURCE	41
FIGURE 24 PLOT SHOWING VARIATION OF DEFECT AREA OBTAINED USING 500 W SOURCE	42
FIGURE 25 COMPARISON OF DEFECT AREAS OBTAINED USING 1000 W SOURCE.....	42
FIGURE 26 COMPARISON OF DEFECT AREAS OBTAINED USING 2000 W SOURCE.....	42
FIGURE 27 A FLOWCHART OF METHODOLOGY TO DEVELOP INDIRECT METHOD TO CALCULATE DEFECT DEPTH	45
FIGURE 28 (A) 3D VIEW OF DISCRETIZED FEM MODEL WITH INBUILT DEFECTS (B) PLAN VIEW OF DEFECTS WITH GRIDLINES	47
FIGURE 29 LOCK IN INFRARED THERMOGRAPHY USING SINUSOIDAL WAVE FOR THERMAL EXCITATION OF CONCRETE SLAB	49
FIGURE 30 THERMAL IMAGE OF THE SLAB SURFACE OBTAINED FROM SIMULATION	50
FIGURE 31 A) VERTICAL SECTIONS ACROSS THE DEPTH OF SLAB B) CROSS SECTION CUTTING DEFECT LOCATION AT THREE PLACES.....	51

FIGURE 32 TYPICAL TEMPERATURE CONTOUR ON VERTICAL SECTION AT LOCATION OF DEFECTS.	51
FIGURE 33 THERMOGRAMS AT A) 2.5 MINUTES B) 7.5 MINUTES C) 17.5 MINUTES D) 60 MINUTES	53
FIGURE 34 SURFACE TEMPERATURE VARIATION AFTER 60 MINUTES THERMAL EXCITATION....	53
FIGURE 35 THERMOGRAMS AT A) 2.5 MINUTES B) 7.5 MINUTES C) 17.5 MINUTES D) 60 MINUTES	55
FIGURE 36 SURFACE TEMPERATURE VARIATION AFTER 60 MINUTES THERMAL EXCITATION....	56
FIGURE 37 THERMOGRAMS AT A) 7.5 MINUTES B) 17.5 MINUTES C) 60 MINUTES	57
FIGURE 38 SURFACE TEMPERATURE VARIATION AFTER 60 MINUTES THERMAL EXCITATION....	58
FIGURE 39 THERMOGRAMS AT A) 7.5 MINUTES B) 17.5 MINUTES C) 60 MINUTES	59
FIGURE 40 SURFACE TEMPERATURE VARIATION AFTER 60 MINUTES THERMAL EXCITATION...	60
FIGURE 41 PERCENTAGE ERROR BETWEEN ACTUAL DEPTH OF DEFECT AND DEPTH OBTAINED FROM SIMULATION	61
FIGURE 42 FLOWCHART OF METHODOLOGY TO DEVELOP DIRECT METHOD TO OBTAIN DEFECT DEPTH	63
FIGURE 43. CASTING OF THE CONCRETE SLAB.....	65
FIGURE 44 A) FRONT SURFACE OF THE SLAB SHOWING THE LAYOUT OF THE PLANNED SUBSURFACE DEFECTS IN THE CONCRETE SLAB (B) SECTION AA (C) SECTION BB (D) SECTION CC (E) SECTION DD	67
FIGURE 45 EXPERIMENTAL SETUP WITH A RECORDING TYPE INFRARED CAMERA.....	68
FIGURE 46 SELECTION OF REGIONS OF INTEREST (ROIs) ACROSS AND SOUND AREAS.....	71
FIGURE 47 ABSOLUTE THERMAL CONTRAST VARIATION - 10 MIN HEATING REGIME	73
FIGURE 48 ABSOLUTE THERMAL CONTRAST VARIATION - 10 MIN HEATING REGIME (SECOND SET OF EXPERIMENTS).....	75
FIGURE 49 VARIATION OF OBSERVATION TIME WITH DEPTH IN THE 10 MINUTE HEATING REGIME	75
FIGURE 50 ABSOLUTE THERMAL CONTRAST VARIATION – 20 MINUTE HEATING REGIME	76
FIGURE 51 ABSOLUTE THERMAL CONTRAST VARIATION - 20 MIN HEATING REGIME (SECOND SET OF EXPERIMENTS).....	77
FIGURE 52 VARIATION IN OBSERVATION TIME WITH RESPECT TO THE DEPTH OF 20-MINUTE HEATING REGIME.....	78
FIGURE 53 A) 3D MESHED FEA MODEL B) PLAN VIEW SHOWING DEFECTS.....	79
FIGURE 54 COMPARISON OF MAXIMUM TEMPERATURES OBTAINED FOR DEFECT D4.....	80
FIGURE 55 A) THERMOGRAM FROM AN INFRARED CAMERA B) THERMOGRAM FROM AN FEA SIMULATION WITH 10 MIN OF HEATING	81
FIGURE 56 VARIATION IN THE DEPTH OF THE DEFECT (D) WITH $(AT_{MAX})^{0.5}$	82
FIGURE 57 COMPARISON BETWEEN THE PREDICTED DEPTH AND ACTUAL DEPTH WITH RESPECT TO PERCENTAGE ERROR.....	84
FIGURE 58 A) 3D MESHED FEA MODEL B) PLAN VIEW SHOWING DEFECTS.....	86
FIGURE 59 ABSOLUTE THERMAL CONTRAST VARIATION A) DEFECT DEPTH 6 CM (50% OF TOTAL DEPTH) B) DEFECT DEPTH 8 CM (67% OF TOTAL DEPTH) C) DEFECT DEPTH 10 CM (83% OF TOTAL DEPTH).....	87
FIGURE 60 COMPARISON BETWEEN THE PREDICTED DEPTH AND ACTUAL DEPTH CONCERNING PERCENTAGE ERROR.....	88

FIGURE 61 FLOWCHART OF METHODOLOGY TO LOCATE DEEPER DEFECTS IN CONCRETE BY USING POST PROCESSING TECHNIQUES	91
FIGURE 62 GUI OF MATLAB POST PROCESSING PROGRAM	94
FIGURE 63 A) LAYOUT OF DEFECTS IN SLAB B) RAW THERMAL IMAGE C) PROCESSED IMAGE – 10 MINUTE HEATING REGIME	95
FIGURE 64 A) RAW THERMAL IMAGE B) PROCESSED IMAGE – 20-MINUTE HEATING REGIME....	96
FIGURE 65 A) LAYOUT OF DEFECTS B) RAW THERMAL IMAGE C) PROCESSED IMAGE – 10-MINUTE HEATING REGIME	98
FIGURE 66 A) RAW THERMAL IMAGE B) PROCESSED IMAGE – 20-MINUTE HEATING REGIME....	99
FIGURE 67 A) LAYOUT OF DEFECTS B) RAW THERMAL IMAGE C) PROCESSED IMAGE – 10-MINUTE HEATING REGIME	100
FIGURE 68 A) RAW THERMAL IMAGE B) PROCESSED IMAGE –20-MINUTE HEATING REGIME ..	101
FIGURE 69 AMPLITUDE (LEFT) AND PHASE (RIGHT) PROFILES PRODUCED BY THE FOURIER TRANSFORM ON A PIXEL'S TEMPERATURE RESPONSE (ADAPTED FROM IBARRA-CASTANEDO, 2005).....	102
FIGURE 70 A) LAYOUT OF DEFECTS B) RAW THERMAL IMAGE C) PHASE IMAGE – 10-MINUTE HEATING REGIME	104
FIGURE 71 A) RAW THERMAL IMAGE B) PHASE IMAGE – 20-MINUTE HEATING REGIME.....	104
FIGURE 72 A) RAW THERMAL IMAGE B) AMPLITUDE IMAGE – 10-MINUTE HEATING REGIME .	105
FIGURE 73 A) RAW THERMAL IMAGE B) AMPLITUDE IMAGE – 20-MINUTE HEATING REGIME .	106
FIGURE 74 A) LAYOUT OF DEFECTS B) RAW THERMAL IMAGE C) PROCESSED IMAGE –10-MINUTE HEATING REGIME	108
FIGURE 75 A) RAW THERMAL IMAGE B) PROCESSED IMAGE –20-MINUTE HEATING REGIME ..	109
FIGURE 76 A) LAYOUT OF DEFECTS B) RAW THERMAL IMAGE C) PROCESSED IMAGE –10-MINUTE HEATING REGIME	111
FIGURE 77 A) RAW THERMAL IMAGE B) PROCESSED IMAGE –20-MINUTE HEATING REGIME ..	111
FIGURE 78 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 5 CM SUBJECTED TO 10 MINUTE HEATING REGIME	112
FIGURE 79 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 3 CM SUBJECTED TO 10 MINUTE HEATING REGIME	113
FIGURE 80 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 2 CM SUBJECTED TO 10 MINUTE HEATING REGIME	113
FIGURE 81 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 5 CM SUBJECTED TO 20 MINUTE HEATING REGIME	114
FIGURE 82 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 3 CM SUBJECTED TO 20 MINUTE HEATING REGIME	114
FIGURE 83 PLOT OF VARIATION OF SNR FOR DEFECTS AT DEPTH OF 2 CM SUBJECTED TO 20 MINUTE HEATING REGIME	115
FIGURE 84 A FLOWCHART OF METHODOLOGY TO COMPARE INFRARED THERMOGRAPHY AND ULTRASONIC PULSE ECHO (UPE) METHOD	117
FIGURE 85 PUNDIT PD 8050 FOR CT SCANNING OF CONCRETE SLAB.....	118
FIGURE 86 EIGHT CHANNELS OF TRANSDUCERS (SOURCE: PROCEQ SA).....	119
FIGURE 87 SIGNAL EMITTED BY ONE TRANSDUCER PICKED UP BY OTHER TRANSDUCERS (SOURCE: PROCEQ SA).....	119
FIGURE 88 UPE EXPERIMENTAL SETUP.....	120

FIGURE 89 LINE SCAN OF SLAB USING PD8050	121
FIGURE 90 UPE B-SCAN OF CONCRETE SLAB	121
FIGURE 91 DEFECT LOCATIONS ON THE SURFACE OF SLAB.....	122
FIGURE 92 COMPARISON BETWEEN THERMAL IMAGE AND LINE SCAN OF SAME CONCRETE SLAB.	122
FIGURE 93 A-SCAN OF SURFACE. RED BOX SHOWS THE EXTENT OF AREA SCANNED.	123
FIGURE 94 LINE SCAN ALONG RED BOX 1	123
FIGURE 95 A-SCAN OF SURFACE. RED BOX SHOWS THE EXTENT OF AREA SCANNED.	124
FIGURE 96 LINE SCAN ALONG RED BOX 2	124
FIGURE 97 A-SCAN OF SURFACE. RED BOX SHOWS THE EXTENT OF AREA SCANNED.	125
FIGURE 98 LINE SCAN ALONG RED BOX 3	125
FIGURE 99 A-SCAN OF SURFACE. RED BOX SHOWS THE EXTENT OF AREA SCANNED.	126
FIGURE 100 LINE SCAN ALONG RED BOX 4	126
FIGURE 101 A-SCAN OF SURFACE. RED BOX SHOWS THE EXTENT OF AREA SCANNED.	127
FIGURE 102 LINE SCAN ALONG RED BOX 5	127

List of Tables:

TABLE 1 DETAILS OF DEFECTS PLACED IN SLAB	24
TABLE 2 QUANTITY OF MATERIALS USED FOR CASTING THE SLAB	24
TABLE 3 SPECIFICATIONS OF FLIR E6 THERMAL IMAGER.....	26
TABLE 4 RESULTS OF TESTING OF ALGORITHM TO CALCULATE DEFECT AREA	26
TABLE 5 THERMAL CONDUCTIVITY VALUES OF CONCRETE AT DIFFERENT TEMPERATURE	30
TABLE 6 PROPERTIES USED FOR THE MODEL	31
TABLE 7 MATERIAL PROPERTIES ASSIGNED IN THE MODEL	33
TABLE 8 COMPARISON BETWEEN DEFECT AREA OBTAINED FROM EXPERIMENT AND ACTUAL DEFECT AREA	35
TABLE 9 COMPARISON OF SURFACE TEMPERATURES FOR DIFFERENT HEATING TIMES	38
TABLE 10 COMPARISON BETWEEN ACTUAL AREA AND DEFECT AREA OBTAINED FROM EXPERIMENT AND FEA SIMULATION	38
TABLE 11 COMPARISON OF DEFECT AREAS OBTAINED FROM PARAMETRIC STUDY	39
TABLE 12 DETAILS OF DEFECTS	48
TABLE 13 DETAILS OF MATERIAL PROPERTY USED IN FEM MODEL FOR SIMULATION OF LOCK-IN THERMOGRAPHY.....	48
TABLE 14 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 20 MM FROM SURFACE OF WAVE TYPE I.....	54
TABLE 15 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 30 MM FROM SURFACE OF WAVE TYPE I.....	54
TABLE 16 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 20 MM FROM SURFACE OF WAVE TYPE II	56
TABLE 17 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 30 MM FROM SURFACE OF WAVE TYPE II	56
TABLE 18 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 20 MM FROM SURFACE OF WAVE TYPE III	58
TABLE 19 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 20 MM FROM SURFACE OF WAVE TYPE III	58

TABLE 20 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 20 MM FROM SURFACE OF WAVE TYPE IV	60
TABLE 21 COMPARISON BETWEEN ACTUAL AND MEASURED VALUES OF DEPTH FOR DEFECTS LOCATED 30 MM FROM SURFACE OF WAVE TYPE IV	60
TABLE 22 QUANTITY OF MATERIALS USED FOR CASTING THE SLAB	65
TABLE 23 SIZES OF DEFECTS EMBEDDED IN THE SLAB	66
TABLE 24 TECHNICAL SPECIFICATIONS OF THE FLIR A325 INFRARED CAMERA.....	69
TABLE 25 MATERIAL PROPERTIES USED IN THE FEA MODEL	79
TABLE 26 COMPARISON BETWEEN THE ACTUAL DEPTH AND THE DEPTH PREDICTED FROM EQUATIONS 13 AND 14	83
TABLE 27 SIZES OF DEFECTS EMBEDDED IN THE FEA SLAB MODEL	86
TABLE 28 COMPARISON BETWEEN THE ACTUAL DEPTH AND THE DEPTH CALCULATED USING EQUATIONS 13 AND 14	88
TABLE 29 FORMAT OF 3D MATRIX FOR POSTPROCESSING.....	93
TABLE 30 COMPARISON BETWEEN ULTRASONIC PULSE ECHO (UPE) AND INFRARED THERMOGRAPHY (IRT) METHOD (JANKU ET AL., 2019).....	128

Chapter 1

Introduction

1.1 General

The concrete structures during their lifetime are exposed to environmental conditions, fatigue, corrosion of reinforcement, etc which leads to damage and affects their functional use. Hence it is vital to conduct timely testing and maintenance. The defects in concrete structures can occur at any time during their service life (*Milovanović & Banjad, 2014*). They reduce the strength and integrity of concrete structures. Several Non-destructive Testing (NDT) methods like rebound hammer and ultrasonic pulse velocity are currently adopted for structural audit and evaluation. These methods require access to the surface of object which is sometimes not available. Infrared thermography (IRT), Ground penetrating radar (GPR) and many more methods can be efficiently used in identifying internal defects (*Oh et al., 2012*), (*Naik et al., 2022*). The infrared thermography method can be used for the location of moisture in concrete and brickwork, the location of voids and delaminations, unfilled joints in brickwork and other defects (*Maierhofer et al., 2003*). In the current research infrared thermography is investigated as a Non-destructive Testing (NDT) method for concrete. It is a non-contact technique that involves scanning of the surface and a thermal camera to capture thermal images (thermograms) of the surface. The infrared thermography method is most useful for locating and identifying sub-surface defects.

The infrared thermography (IRT) technique uses a thermal camera to detect infrared radiation emitted by objects. Infrared radiation is emitted by all objects with surface temperatures above absolute zero. The infrared radiation is invisible to the human eye but can be felt as heat. The infrared radiation is categorized into IR-A (0.78 μm -1.4 μm), IR-B (1.4-3 μm) and far-IR (3 μm -10 μm). Most of the infrared radiation is absorbed by the air molecules in the atmosphere. The radiation in the wavelength range of 1-3 μm and 5-10 μm gets transmitted by atmosphere. These wavelengths can be detected by an infrared camera using a network of sensors. The sensors in an infrared camera collect surface temperature data and store it in pixel form to generate an image. However, some high-end cameras can store temperature data of the object's surface as a video sequence. The infrared thermography technique is now widely used in the construction field due to its ability to quickly scan and locate internal defects in concrete structures (*Hiasa et al., 2017*). This technique has successfully demonstrated its ability to detect defects in concrete structures and has been published in multiple studies by (*Cotic et al., 2015*), (*Meola, 2007*), (*Maierhofer et al., 2006*), (*Hiasa et al., 2018*), (*Adeli & Sirca, 2018*) and (*Yehia et al., 2007*).

A few studies that used infrared thermography for Non-destructive Testing (NDT) are mentioned. *Milovanović & Banjad, (2014)* used stepped infrared thermography for the inspection of concrete structures. The thermal images recorded are subjected to the Fast Fourier Transform method whose output is phase image and amplitude image. The authors found that the phase images display clear images at an optimal discrete frequency while the amplitude images are affected by uneven heat distribution. Infrared thermography (IRT), ground-penetrating radar (GPR), and many other methods can be efficiently used to identify internal defects (*Oh et al., 2012*). An experimental study was conducted by *Cheng et al. (2008)* to compare the capability of infrared thermography, impact echo and ground penetrating radar to locate defects in concrete bridges. The authors used these methods to conduct experiments on three specimens with defects and three specimens without defects. Thus, it was concluded that IRT is fast with live results. This was further confirmed by *Aggelis et al. (2020)* and *Sirieux et al. (2007)*. *Sirieux et al. (2007)* used the IRT technique for detecting damage in real concrete structures and compared it with the electrical resistivity and capacitor method. The authors concluded that IRT is a quick method to give general measurements which can be later used to deepen investigations. *Vaghefi et al. (2011)* reviewed several research papers and concluded that IRT can greatly enhance concrete bridge inspection.

Maierhofer et al. (2003) successfully applied infrared thermography to locate moisture in concrete and brickwork, voids and other inhomogeneities and unfilled joints in brickwork. The infrared thermography technique is widely used in the construction field because it can quickly scan and locate sub-surface defects in concrete structures (*Hiasa et al., 2017*). The size and shape of defects inside concrete affects their depth identification (*Cotic et al., 2015*). The infrared thermography technique has been integrated with other methods to detect defects in concrete structures. *Aggelis et al. (2020)* utilised infrared thermography to detect near-vertical cracks and paired with ultrasound to locate the depth of defect. The defect areas were located by plotting temperature data of the surface. *Yehia et al., (2007)* concluded that infrared thermography is a fast method with real-time capability. However, infrared thermography is a surface method. The defect's depth and size control the ability of infrared thermography to detect deep flaws. The detectability of infrared thermography also depends on the ambient environmental conditions.

The Non-destructive Testing (NDT) method utilising infrared thermal technology is termed as thermal non-destructive testing (TNDT). Thermal Non-destructive Testing (TNDT) is defined as thermal stimulation of the surface and recording of temperature variation over time using a thermal camera. The recording time includes the heating and cooling phase i.e. after heating

source is turned off. Figure 1 shows a typical TNDT setup consisting of slab with internal defect which is heated using thermal excitation sources. An infrared camera shown in the figure records temperature variation over slab surface. The camera is connected to a computer interface which displays the thermal images. The handheld infrared cameras have their own display interface and do not require computer interface.

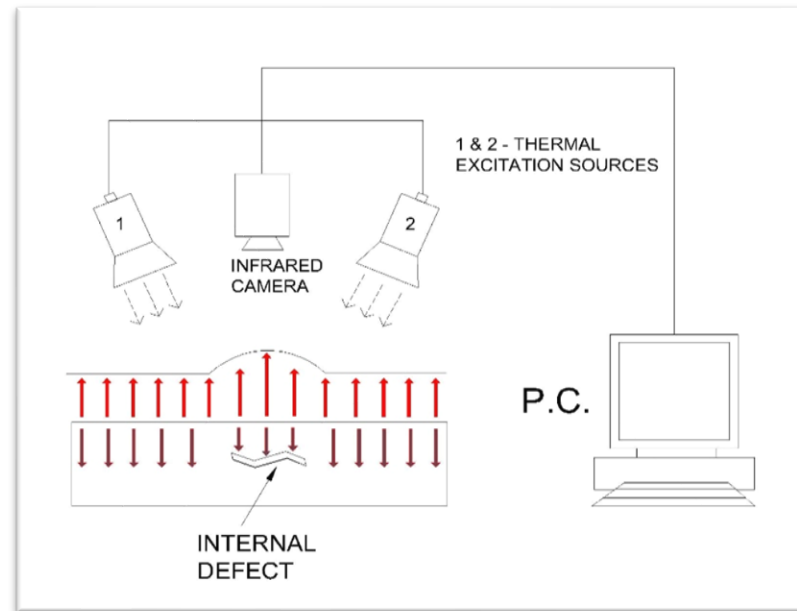


Figure 1 Typical Thermal Non-Destructive Testing (TNDT) setup

The presence of subsurface defects causes deviations in the surface temperature distribution at the defect location as shown in Figure 1. This is because heat flow takes a longer time to travel thus momentarily increasing temperature (*Meola et al., 2007*). The infrared camera displays this temperature variation as thermal hot spot or cold spot. The infrared thermography technique is very well suited for the detection of voids and honeycombing in concrete. The location of delamination's in multi-layered systems (e.g. plaster on concrete, CFRP-laminates on concrete, asphalt on concrete) is also possible with infrared thermography. The defects like voids in tendon ducts and cracks in concrete could be recognised by *Mairhofer et al., (2006)* while debonding in concrete bridge decks could be detected by *Adeli & Sirca, (2018)* using infrared thermography. *Scalbi et al., (2019)* used laser spot thermography to evaluate fractures in concrete slab along with FEA simulations.

Infrared Thermography is classified into passive thermography and active thermography. In passive thermography, the infrared images of the object are captured under ambient conditions. The maintenance works like electronics and electrical parts inspection, power line inspection, fire detection, etc. are passive thermography's main application areas. In active

thermography the object under test is subjected to external heating. This method causes all the hidden defects to reveal themselves. Depending on the temporal nature of the heating, active thermography is further divided into a number of categories. *Milanovic et al., (2016)* explored and reviewed methodologies that use natural excitation sources and active thermography. They are stepped, lock-in and pulsed infrared thermography. A new active thermography technique called Frequency modulated thermal wave imaging (FMTWI) was introduced by *Chatterjee (2011)* in his studies on aluminium test samples with defects. The types of infrared thermography like stepped, lock-in and pulsed infrared thermography were utilised in the current work to predict the area as well as depth of subsurface defects. In pulsed infrared thermography, an object being tested is subjected to a short burst of a high-energy pulse. The duration of the pulse can be between a few μs to seconds. The pulse increases the surface temperature of the object. The variation in surface temperature of the object with time is recorded by an infrared camera. The stepped infrared thermography technique also called long pulsed thermography is the simplest form of active thermography. In this technique, the test sample is subjected to a continuous heat source, and thermogram video recording is started at $t = 0$. In lock-in thermography the object under examination is subjected to periodic heating and cooling at a fixed frequency. The images are recorded when steady state is reached.

The active infrared thermography technique was utilized to detect defects in post-tensioned ducts using a shortwave infrared heater by *Shengli et al., (2024)*. The authors applied thermal radiation with an intensity of 550 W/m^2 and a heating duration of 45 minutes followed by a cooling period of 90-130 minutes. This methodology could detect defects upto depths of 50, 70 and 90 mm from the surface. The study referenced above has explored methodologies to integrate defect depth detection into predictive models. The knowledge of depth of defect from surface and size helps in optimising repair costs and material usage. It enables the concrete structure to be repaired immediately if there is a symptom of damage during regular monitoring using infrared thermography. Hence infrared thermography monitoring gives benefit of condition-based maintenance which is sustainable rather than repetitive maintenance. The techniques like stepped, pulsed thermography and lock-in thermography are explored in the current study. A technique is developed to obtain the area of sub-surface defects in concrete structures using thermograms. Further the research is focused on direct and indirect methods to obtain the depth of sub-surface defects in concrete. The study also explores methods to eliminate noise in thermal images and to identify deeper defects. A comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) method is also presented in this thesis.

1.1.1 Stefan's law of radiation

This law was proposed by Austrian physicist Joseph Stefan who stated that “Any body having absolute temperature above zero radiates heat per unit area per unit time proportional to the fourth power of absolute temperature of the body”. As per Stefans law, the heat energy H emitted by any object is given by Equation 1 below:

$$H = \sigma T^4 \quad (1)$$

where σ is Stefan's constant = $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ and T = absolute temperature of the body. A body which follows the above-mentioned law is defined as a black body. However perfect black body does not exist in real life. Emissivity (ϵ) is defined as the ratio of heat emitted by a real object at a given temperature to heat radiated by a black body at the same temperature as given in Equation 2:

$$\epsilon = \frac{H_{obj.}}{H_{black\ body}} \quad (2)$$

1.1.2 Wien's displacement law

The waves having wavelength longer than that of red light are known as infra-red (IR) waves and are mostly emitted by bodies at higher temperature. The intensity vs. wavelength plot for a hot body is shown in Figure 2 below. The intensity of the radiation emitted by a body is maximum at a specific wavelength which is the characteristic of temperature. As temperature increases the peak maximum shifts towards the lower wavelength. This is known as Wien's displacement law. The total amount of radiated energy is equal to the area under the curve. The area also increases with temperature as suggested by Stefan's law.

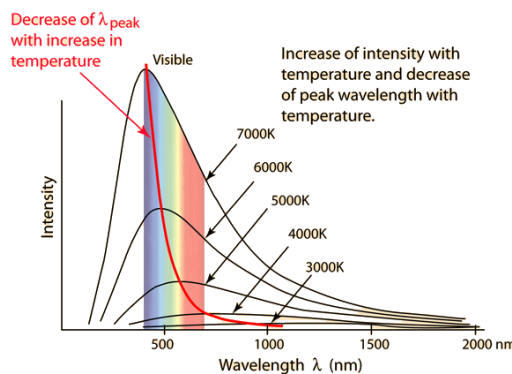


Figure 2 Intensity v/s wavelength plot for a hot body at different temperatures (Wiens displacement law) (Source: S. Gabriel Pfaffman)

1.1.3 Infrared (IR) camera

An infrared camera is like any ordinary camera except that it has sensors which respond to Infrared or near Infrared radiation. The output of such a camera is a grayscale image

representing numbers which describe intensity of temperature received at respective pixels. Such an image is known as thermogram. IR camera has lenses which are transparent to IR radiation like Germanium, Telluride, etc. Higher versions of these cameras have cooling systems for the sensors which can get heated and add its own temperature to the output. The grayscale images are difficult to read and hence displayed in pseudo-colour format where each temperature is matched to a specific colour. A typical thermal image in pseudo-colour format is shown in Figure 3 below.

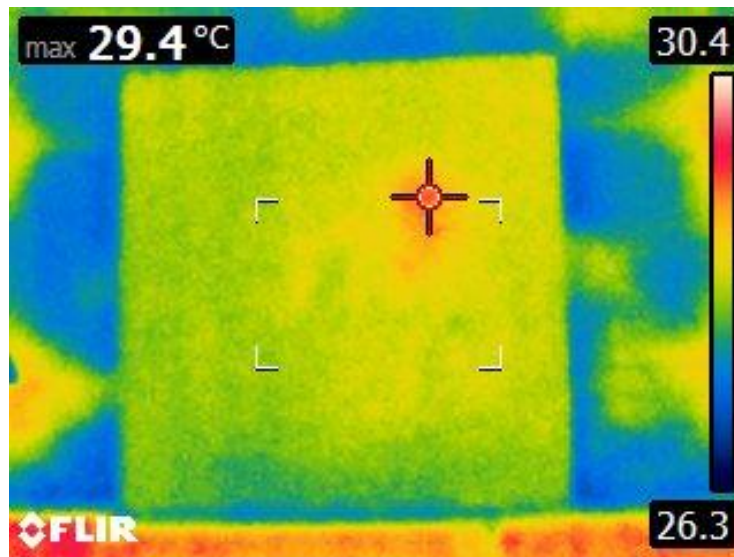


Figure 3 Typical coloured thermogram of a RCC slab captured using FLIR E6 hand-held Infrared camera

1.2 Types of Active Infrared Thermography

1.2.1 Stepped Thermography

This is simplest form of active thermography. In this technique test sample is subjected to a continuous heat source, and the thermogram video recording is started at $t = 0$. It is also called long pulsed thermography. The heat is absorbed by the sample which raises the temperature of the surface. As a result, heat gets conducted into the inner layers of the sample due to the temperature difference. The rate of heat conduction is not only dependent on this temperature difference, but also on the properties of the test sample. In a sample without defects the heat is carried away equally well from all parts of the surface, hence the rise in surface temperature is expected to be identical over the entire surface. However, if there is the presence of a void, the heat transfer is not uniform. In such a case the temperature over defective region becomes different compared to the sound area which can be recorded by Infrared camera.

The drawback of this technique is the excessive overheating of the test sample. In addition, the spatial resolution suffers significantly due to lateral diffusion of heat. Hence this technique tends to be effective for big structures with large defects, and is used primarily by civil engineers as found by *Tuli S. (2011)*.

1.2.2 Pulsed Thermography

In this type of thermography, the object under test is subjected to a short burst of high energy pulse. The duration of the pulse can be between a few μ -secs to a few seconds. The pulse immediately increases the surface temperature and the variation of surface temperature with time is recorded. This can be explained using 1-D heat equation by Fourier as studied by *Tuli S. (2011)*. The Figure 4 below shows temperature vs time variation on the surface of an object subjected to a pulse. The blue curve indicates temperature distribution of sound area and red curve indicates temperature distribution of defect area. It is seen from Figure 4 that temperature over defect region is higher as compared to sound area.

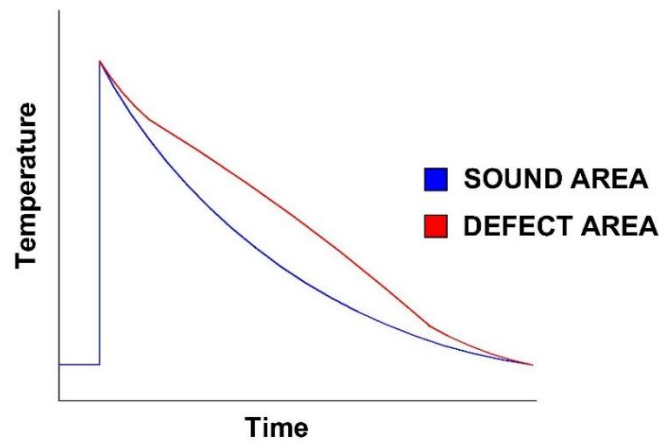


Figure 4 Plot of temperature v/s time for a surface after application of heat pulse

The peak value of temperature is obtained after which it decays exponentially over time. The Equation 3 shows heat flow equation.

$$k \frac{d^2 T}{dx^2} = \rho C^H \frac{dT}{dt} \quad (3)$$

where T is temperature at depth x below the surface at time t and ρ , C^H and k are density, heat capacity and thermal conductivity of the object. The solution of this equation under a Dirac delta pulse of thermal energy of magnitude H_p on the surface, at $t = 0$ is given by Equation 4:

$$T(x, t) = \frac{H_p}{(\pi \rho C^H k t)^{1/2}} e^{\frac{-x^2}{4\alpha t}} \quad (4)$$

where $\alpha = k/(\rho C^H)$ is known as thermal diffusivity of the material.

It is effective for planar defect detection where the defect plane is reasonably parallel to the sample's surface. However, pulse thermography may fail to identify the presence of micro

cracks or of surface breaking cracks that run perpendicularly to the surface because they have little effect on the heat flow generated by the flash lamp.

1.2.3 Pulsed-Phased Thermography

A pulsed excitation can be thought as a superposition of a large number of periodic sinusoidal excitations as shown in Figure 5. Thus, when an image obtained using pulsed thermography is processed with Fourier transformation, we obtain phase and amplitude images. The images are drawn corresponding to each of the analysis frequencies. This analysis method was named pulsed phase thermography (PPT) by *Maldague & Galmiche*, (2001). The defects at different depths become visible at different frequencies in the form of phase images and amplitude images. The phase image solves the problem of non-uniform heating of the specimen, and also the problem with the reflectivity which proved to be significant regardless of the high emissivity of concrete and appears on the thermograms. The amplitude images are affected by uneven heating of the specimens thus proving themselves to be inferior compared to the phasegrams as found by *Milovanovic & Banjad*, (2014).

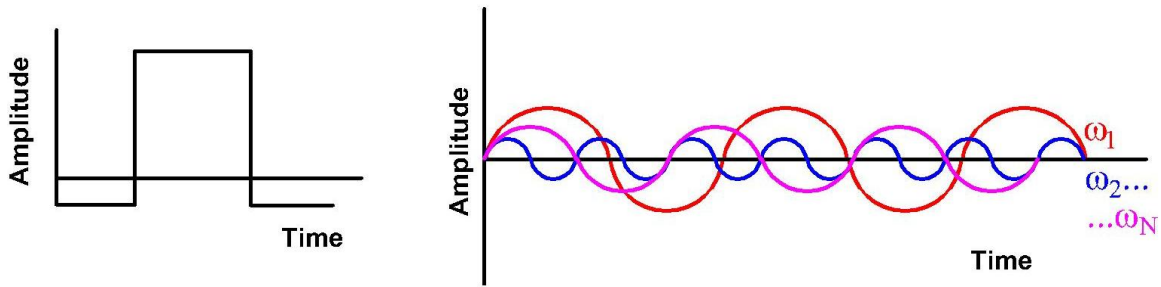


Figure 5 Pulsed excitation

1.2.4 Lock-in Thermography

The object under examination is subjected to periodic heating and cooling at a fixed frequency. The images are recorded when steady state is reached. However, thermograms obtained using Lock-in Thermography in raw form cannot detect any defects and hence need processing. This is explained using 1-D heat equation by *Chatterjee*, (2011). The frequency applied on the surface of object takes the form of thermal wave having amplitude and phase travelling perpendicular to the body of the form shown in equation 5:

$$T(x, t) = T_0 e^{\frac{-x}{\mu}} \cos\left(\omega t - \frac{2\pi x}{\lambda}\right) \quad (5)$$

where T_0 is amplitude of temperature oscillation at the surface, μ is thermal diffusion length and λ is wavelength of thermal wave. There exists an amplitude and phase difference between the response of defect area and that of sound area. The AC component of recorded data at the

given frequency of every pixel is subjected to Fourier Transform which gives rise to amplitude and phase images shown in Figure 6.

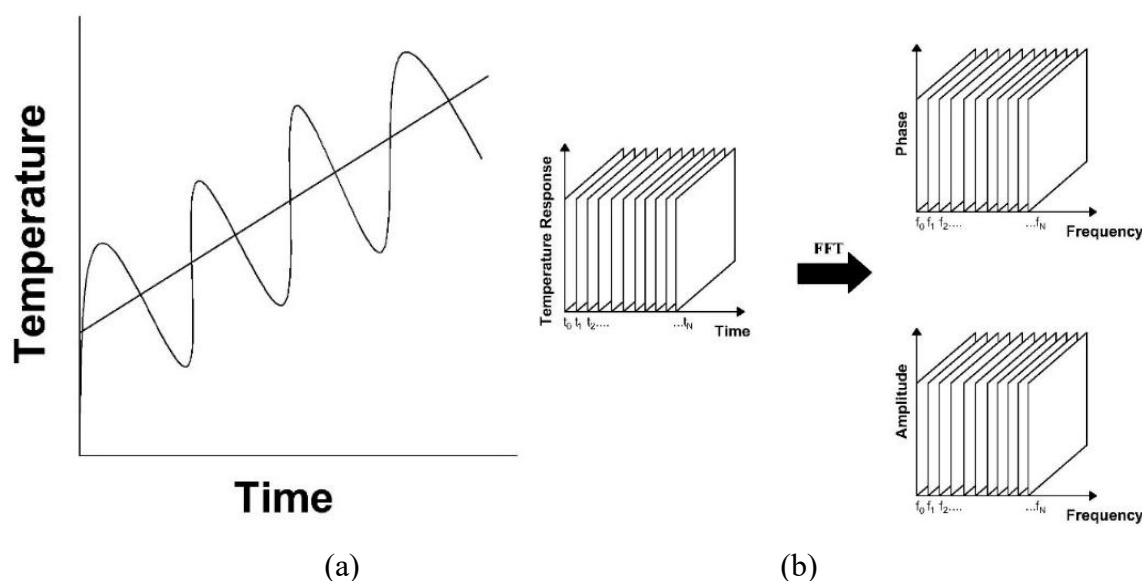


Figure 6 a) Increasing trend of plot represents DC component while wavy pattern represents AC component b) Phase image and Amplitude image

1.3 Numerical simulation

The finite element techniques are integrated and used in commercially available software. These softwares are extremely simple to adopt and enable the precise 3-dimensional geometries to be modelled. This ability coupled with the low model run times has enhanced the feasibility of generating a suitable transient thermal solution. In many cases design models will have already been created, and hence need only be calibrated for the thermal analysis. The use of FE simulations provides a uniquely flexible technique combined with the ability of finite element program macros to automatically generate models. The present work investigates the use of two commercially available FEA software to accurately simulate the thermographic inspection of laboratory cast concrete slabs.

Hiasa et al., (2017) utilised FEA simulations to develop a methodology to interpret and detect delaminations in bridges from IR images because of difficulty in identifying just from color contrast. The temperature of sound part was obtained from experiment while temperature of defect area was obtained from FEA simulation. The defects were identified easily by this method but results were affected by boundary conditions and time of data collection. An infrared camera along with matrix of heat sensors was used by *Hiasa et al., (2018)* to determine heat distribution and heat capacity on surface of laboratory cast concrete slab. The FEA simulation of experiment was used to find out influence of embedded steel bars on thermal

response. The FEA simulation can be used to provide useful information about effect of embedded materials on heat transfer in slab. FEA simulations were used along with Infrared Thermography to explore favourable time windows for bridge deck inspection. It is concluded that optimal time for damage detection is night under clear sky condition. The obstacles did not have much effect on results and could be easily distinguished. The FE models of concrete slabs with artificial delamination's were used for more accurate and reliable processing of data by defining criteria for thermal contrast by *Gabriel et al., (2015)*. The thermographic study was performed on GFRP curved composite panels with sub-surface defects which were either artificially induced and from static loading. The FEA model of the experiment was created to model transient heat transfer and results were compared to experimental results. The authors found that the geometry of defects could be located precisely using FEA simulation. An infrared thermography experiment on a concrete slab with inbuilt defects was simulated in FEA software and subjected to time varying thermal excitation by *Naik et al., (2022)*. The depth of the defect was determined by taking vertical sections and plotting temperature contours. The depth of defects with different thicknesses could be determined with up to 2% error.

1.4 Motivation and objective of thesis

In many research works, the application of infrared thermography is detection of water leakages, inspection of electrical conduits and bridge decks. The thermal images can only reveal location and extent of damage. This research aims to develop methods to derive additional information like area and depth of defects from thermal images which need image processing. The estimation of the cost of repair work requires the calculation of the percentage of damaged area. The depth of the defect is also an important factor in determining the type of repair method to be adopted. *Huh et al., (2018)* derived an equation to calculate the depth of defect which was based on the thermal contrast method. It is understood from various literature works that thermal images are affected by non-uniform thermal excitation and emissivity. In such cases, post post-processing techniques filter out noise and enhance the thermal images. This research used post processing techniques to reveal deeper defects. Based on the gaps identified following objectives were formulated:

- To improvise non-contact techniques for detecting defects in concrete and calculate the area of damage using Infrared Thermography (IRT).

- To devise a technique to calculate the depth of sub-surface defects in concrete structures based on their properties.
- To eliminate noise in images caused due to non-uniform heating and reflection in concrete by using Infrared Thermography (IRT).
- To compare IRT with other compatible Structural Health Monitoring (SHM) techniques.

Chapter 2

Literature Review

2.1 Introduction

The infrared thermography technique has the potential to be an effective NDT method to detect cracks at local level in structures as well as global level. The Non-destructive testing using IR thermography generally consists of excitation of the object under examination and monitoring of its surface temperature variation during the transient heating or cooling phase. The excitation can be photo thermal (Halogen lamps, Lasers, etc.), heat sources or even mechanical vibrations which induce change in temperature of the object. The existence of defects in the object affects the heat transfer and thus causes local changes of temperature distribution on the surface of the observed structure, which is then recorded using an IR camera.

2.2 Literature summary

Hiasa et al., (2017) developed a methodology to interpret and detect delamination's. The authors utilized Finite Element simulations to explore threshold for thermal data processing. The authors have cast four concrete blocks of 91.4 x 91.4 x 20.3 cm with defects of 10.2 x 10.2 x 0.3 cm size at depths of 1.27 cm, 2.54 cm, 5.08 cm and 7.62 cm from surface. Three types of infrared cameras are used to record thermal images of surface of concrete over 24-hour time period. The temperature of the sound part of concrete block was obtained from experiment and of delaminated part was obtained from FEA simulation. The thermal contrast between the sound and delaminated part of concrete is calculated over time. The thresholding technique is developed where if the temperature of a point is lower than temperature of the delaminated area then it is displayed in black colour. The thermal contrast is added or subtracted from the temperature of the delaminated area depending on the time of day. The thermal images are processed using this methodology and it is found that defects upto a depth of 1.27 cm and 2.54 cm could be identified. It is found that thermal contrast is maximum at 3 pm and minimum at 9 am. The integrated use of infrared thermography with Finite Element simulation can improve the efficiency of defect detection.

Pedram et al., (2022) cast six concrete slabs with predetermined void depths and used convective heating and cooling as thermal excitation. An experimental study was performed to study the variation of thermal contrast with depth of defect under heating and cooling and initial surface temperature. A multivariate statistical model developed in this study represented the variation of thermal contrast with defect depth and initial surface temperature. The

presented statistical model calculated thermal contrast for thicker defects only up to 25 mm depth.

Hiasa et al., (2018) explored favourable time windows for concrete bridge deck inspections using IRT and Finite Element simulations. The authors used a slab with embedded defects from earlier study having delamination's at 1.3 cm, 2.5 cm, 5.1 cm and 7.6 cm. The obstacles like wooden chips and gravel were stuck on to the slab surface. Thermocouples were utilized to get accurate temperature. The infrared camera records thermal images of the surface at one hour interval over a 24-hour time period. The effect of debris on defect detection is investigated. The results showed that there are interchange periods during daytime heating and night time cooling effect. The defects could not be detected during interchange period and adjustment of temperature setting on camera is required for different areas of slab. It is concluded that night time cooling cycle is more favourable than the daytime heating. Debris can be easily identified by comparing infrared and HD images. Also, there is no effect of debris on quality of infrared image as they heat and cool down faster owing to small surface area.

Hiasa et al., (2017) modelled concrete slab with delamination's from an earlier study in FEM software. The authors used heat transfer models to explore sensitive parameters for the effective utilization of IRT. The FE model developed is validated with experimental results by correlation of surface temperatures from simulation and thermal cameras. FE modelling results showed that FEM analysis can effectively locate the defects if thermal contrast is in range of 0.3-0.4°C. The study shows that area of defect has more influence on detectability than thickness and volume. The validated FE models can be used to predict the defect depth before field inspection is carried out thus reducing time. The FE models can also be utilized for more reliable processing of data by defining criteria for thermal contrast. The FEM model can be used to reduce experimentation and increase the reliability of data.

Pozzer et al., (2024) utilized passive infrared thermography to explore concrete samples with artificial damages for a period of 24 hours over three seasons. Three concrete specimens were cast to simulate different structural members of public infrastructure: one reinforced slab, one non-reinforced slab, and one reinforced column. The slab specimens were 400 × 600 × 150 mm, while the column specimen was 220 × 320 × 1500 mm. Polystyrene is used to simulate air voids since its thermal conductivity (0.027 W/m°C) is close to air (0.024 W/m°C). Each slab sample had six square-shaped subsurface defects of 100 and 50 mm placed between 15 and 70 mm from the concrete surface. The column also had six sub-surface defects on each face, with rectangular (150 × 130 mm) and square (80 × 80 mm) shape defects, placed between

20 and 85 mm depth from the concrete surface. The authors found that the passive IRT technique was able to detect delamination on reinforced concrete slabs with S/D ratios of up to 2.0 using the thermal contrast method. The signal processing techniques make it possible to identify defects with an S/D ratio up to 1.7 which is a 15% improvement over the thermal contrast method. It is observed that the contrast in the reinforced specimens was slightly lower than that observed in the non-reinforced ones when examining identical defect configurations. The technique employed by authors could identify subsurface damages up to 80 mm in concrete structures with a width-to-depth ratio of up to 1.0. The analysis of passive IRT sequences by signal processing techniques improved defect detectability by more than 10% in most of the investigated specimens.

Gu J.C et al., (2020) studied four Reinforced Cement Concrete (RCC) specimens coated with mortar and CFRP with embedded artificial delamination's based on an existing bridge. The authors used active infrared thermography to obtain thermal images of the surface of the concrete specimen. In addition to size of the delamination, the effects of the quantity of water in the delamination and the cover mortar are considered. A method to identify the boundaries and regions of delamination was proposed and studied. The results showed that the detectability of delamination regions that were at least $5\text{ cm} \times 5\text{ cm}$ in size is possible. The presence of surface cover mortar and water decreased the accuracy of the detectability. The method presented in the current study utilized the measurement of the second derivative of temperature, i.e. the location of inflection points to determine boundaries of defects. To apply the method for requirements of periodic inspection or long-term monitoring under harsh environmental conditions, further work is needed to enhance the accuracy of results.

Panella et al., (2020) presented a review and comparison of different thermal image processing methods like common absolute contrast, differential absolute contrast (DAC), principal component thermography (PCT) and thermographic signal reconstruction (TSR). A new processing method is introduced by the author to improve sub-surface defect detection in composites. Thermographic tests were conducted on GFRP plate with numerous flat bottom holes of different size and depths. Tanimoto criterion and SNR were used to assess detectability. In the raw images, large defects are easily observed; however, signal processing techniques such as TSR, DAC, PCT and proposed LBC allow detection of smaller and deeper defects within certain limits.

Huh et al., (2018) conducted studies on a concrete slab with defects at depths ranging from 1 to 8 cm. The slab was subjected to external excitation with varying heating times. The thermal images of the slab are recorded at 10 s intervals using a recording type Infrared camera. Signal

to Noise ratio (SNR) is used as a measure of detectability of defects. The authors determined observation time for defects at different depths by calculating the absolute thermal contrast between defect and noise area. It is observed that as depth of a defect increases the SNR value decreases. It is also observed that higher the heating time, higher will be the SNR. The authors derived an equation to predict the depth of delamination using thermal diffusivity and observation time using minimum error. This study has improved upon this equation by considering non-linear variation.

Gabriel et al., (2015) used reinforced concrete slab having a parallelepiped shape with the length and the width equal to 400 mm and a thickness equal to 50 mm. It consisted of an electrical heating source and a steel frame for fixing the slab. For thermal analysis an infrared camera along with array of sensors is used. The experimentally validated model is developed in Comsol Multiphysics to evaluate influence of steel bars in concrete slab during heat transfer process. The paper gives the information to continue the experimentations using infrared thermography and the FEM simulation on other type of systems or materials to determine the heat properties, defects detection, or other anomalies.

Pedram et al., (2024) focused on corrosion defects of embedded rebars in laboratory cast concrete slab. The corrosion is accelerated artificially using an electrical setup. Infrared images were post-processed using a proposed objective thresholding method based on unsupervised k-means clustering. Automated method was developed to classify IR images into defective part by comparing with visual image. The study found threshold thermal contrast values for corrosion induced damage. The study was performed by multiple experiments on concrete slabs of $400 \times 300 \times 150$ mm dimensions having embedded metal rebars.

Yumnam et al., (2021) investigated concrete structures with Fibre Reinforced Plastics (FRP) as external reinforcement and the occurrence of defects. The authors have chosen infrared thermography as an NDT technique and compared it with others. The authors have reviewed Principal Component Analysis (PCA) as post processing method for the improvement of thermal image quality. The authors conclude that infrared thermography is an effective method to locate defects and flaws in FRP bonded concrete structures. Lock in thermography is preferred if defects are located at deeper depths compared to pulse thermography. The thermal contrast method is suitable for shallow defects while PCA can be utilised to remove effects of non-uniform heating. Thermal contrast exists longer for certain types of thermography however there is a threshold above which it ceases. Thermal images are affected by the characteristics of defects like size, depth and composition.

Milovanovic et al., (2016) reviewed the testing methods, equipment and processing methods used in thermographic inspections, and applications in various fields. Passive and active infrared testing methods are compared. Also, a comparison is done between infrared thermography and other methods. The authors concluded that inspection by infrared thermography can significantly reduce the time required since it is a quick scan method. Post-processing methods can be employed to minimize the effects of non-uniform heating.

Sultan & Washer, (2017) conducted Non-destructive Testing on slab of size 6 x 3 x 0.18 m with styrofoam defects representing delamination's to simulate RCC bridge deck. The size of the targets ranged from 15.24 cm x 15.24 cm to 60.96 cm x 60.96 cm. Delamination targets were placed approximately 50 mm from the concrete surface. Thermal camera is used to capture images of laboratory cast slab as well as an in-service bridge deck. The recorded thermal images are compared with visual images on a pixel-by-pixel basis using Receiver Operating Characteristics (ROC). This work presents an improved method for characterizing the reliability of Infrared Thermography (IRT) and determining the optimum thermal contrast for the detection of delamination in concrete. The results of the study demonstrated that the nonparametric estimate of the area under the ROC curve (AUC) was larger than 80% with its 95% confidence for each group of images. The optimum thermal contrast range is determined to be 0.6-0.8°C.

Janku et al., (2019) compared the accuracy, testing practicality, and costs of infrared thermography, ground penetrating radar and ultrasonic pulse echo by applying them to locate cavities in a concrete bridge. For this purpose, a concrete panel of size 1 m x 1 m x 0.22 m is cast with depth of defects ranging from 0.5 to 4 cm. The measurements performed on the concrete bridge revealed the limited capability of GPR to detect cavities located just beneath the surface, while UPE failed to detect such defects completely. On the other hand, IRT was very successful at locating cavities near the surface, but only under convenient weather conditions. As for the accuracy of determining the shape and size of delamination's, IRT and GPR perform similarly provided GPR scans are dense enough and the thermal camera is at optimum distance. Given the nature of the defects and their depth, the most suitable method for this bridge's diagnostics was IRT. Its main advantage is how quickly it could scan the entire bridge without requiring direct access to the structure.

Cotic et al., (2015) conducted infrared thermography experiment along with 3D numerical simulation on different slabs with defects of various sizes and depths. The thermal contrast and phase contrast method were used to develop a statistical method to predict the depth of defect. The authors found that it is possible to detect defects of size D at depth of $0.9D$ using

thermal contrast method and 1.3D using phase contrast method. The defects at depths more than 6 cm could not develop thermal contrast. It is shown that, using the phase contrast method, delaminations with thicknesses as small as 2 mm could be observed beneath 2-3 cm of plaster.

Madruga et al., (2010) used higher-order statistics (HOS) analysis to process IR images of CFRP reinforced samples and compress the information about defects into a unique image for inspection. Higher order statistics showed higher contrast ratio compared to raw thermal image and compress large amount of data sequences.

Rodríguez-Martín et al., (2015) developed a depth prediction model by correlating surface temperature and depth of crack in welded steel. Model can be used to convert temperature values into depth values.

Moskovchenko et al., (2022) utilised the Probability of Detection (POD) function which is function of defect size and depth for detecting defects with different size/depth ratio in 3D printed specimens. The proposed approach has been proven on raw thermographic data although many known processing algorithms, such as Thermal Signal Reconstruction (TSR), Principal Component Analysis (PCA), Pulse Phase Thermography (PPT), etc. may enhance POD. Because of a non-linear character of relationships between calculated parameters (phase, principal component) and defect parameters, this methodology requires further investigation.

Sakagami et al., (2002) developed a quantitative technique to detect size and depth of delaminations based on phase delay using Lock-in thermography. A concrete slab was cast with artificial delamination's and it was subjected to thermal excitation using quartz heater relay. The relay was subjected to sinusoidal heating of varying time period using computer program. The authors found that there is an optimal heating time for every defect depth. It was concluded that location and size of defects can be determined from contrast change in phase images. Defect depth can be determined by using relation between heating period and phase delay time.

Cheng et al., (2008) conducted a study on how infrared thermography can be paired with elastic wave technique. Fast scanning was performed using infrared thermography and spot scanning was performed by impact echo or coin tapping methods. The tests were performed on concrete slab with embedded defects and mock up wall with cladding tiles. Authors found that the temperature difference depends on depth and area of defect. Since infrared image give limited information about depth of defect impact echo method was used. Authors concluded that information on size and depth of defects can be obtained by combining data from both methods.

Omar et al., (2018) developed an automated procedure to identify different types of delaminations in bridge decks. Passive infrared thermography was conducted on the bridge by mounting camera on vehicle. The thermal images were enhanced using image processing techniques and individual images were stitched together to create a mosaic image. The k means clustering technique was utilised to segment the image and develop objective thresholds. A condition map of entire bridge deck is created to identify different categories of delaminations. The infrared thermography results were validated with Ground Penetrating Radar (GPR) technique. The authors conclude that the method developed by them can analyse condition of bridges without human interference and simplify infrared thermography to be implemented in field for condition based maintenance. This method is best suited for passive thermography.

Ishikawa et al., (2013) conducted a study on detection of deeper defects and identifying optimum frequencies to detect defects of particular shape and size. The authors used Pulse Phase Thermography (PPT) method. A polymethylmethacrylate (PMMA) specimen with 12 holes was used as test specimen. It is seen that deeper defects are detected at low excitation frequency because lower frequency dissipated at more distance from surface. The authors investigated at what frequency phase contrast reaches a maximum value for each defect depth and studied signal-to-noise ratios. The work involved finite element analysis and validating results by conducting experiments. It was concluded that signal-to-noise ratio for deeper defects is higher at low frequencies and optimum frequency decreases continuously with increasing defect depth. The method demonstrated in this study can detect defects of maximum size upto 5-6 mm depth from surface which is a slight improvement as compared to previous studies.

Tran et al., (2018) conducted square pulse thermography on concrete specimens with delamination's at various depths to simulate cover in concrete bridge decks. This study investigates the effect of steel bars on detectability of delamination's which width to depth ratio less than or equal to 2. Two concrete specimens are cast out of which one had reinforcement and other was without reinforcement with delamination's of various sizes. The absolute thermal contrast method was used. The authors concluded that absolute contrast reduces slightly under effect of steel reinforcement. The observation times of delamination's below rebars is decreased compared to those above. The authors observed that trend of observation time decreases with increase in heating time for given depth. The results presented in this thesis although suggest otherwise. The authors found that delamination's with width to depth ratio less than 2 were not visible inspite of high heating times.

Yehia et al., (2007) conducted experimental investigation to evaluate ability of infrared thermography, impact echo and ground penetrating radar (GPR) to detect flaws in concrete bridges. Three concrete specimens had artificial voids, cracks and delamination's while other three were used as control specimen. The two parameters considered in this study are depth of defect and size. The authors concluded that infrared thermography is a fast scanning method however its ability to detect defects is controlled by defect depth and size. This is verified from study conducted in this thesis and post processing of thermal images was conducted to tide over this gap. The GPR method is highly sophisticated and is capable of detecting defects but is dependent on antenna type and resolution and minimum detection depth. GPR can detect those defects which are above steel. Also, it is found that defects had to be atleast 13 mm thick to be detected by GPR. The impact echo method is time consuming however it gives reliable results. Care has to be taken in case of rough concrete surfaces as it requires multiple testing points.

Adeli & Sirca, (2018) compared vibration based health monitoring and infrared thermography monitoring of different concrete structures. The authors found that for large structures like dams and cooling towers it is effective to capture thermal images at night when the structure is cooling under ambient conditions. Alternatively, images maybe taken in morning when structure is cooling overnight. Authors suggested to use post processing methods to enhance thermal images when ambient conditions are low. The authors conclude that IRT can detect cracks, voids, delamination, and other anomalies over wide areas of the dam very quickly compared to traditional methods. This is also proven in this thesis.

Tashan & Al-Mahaidi, (2014) conducted experiments on Carbon Fibre Reinforced Polymer (CFRP) concrete samples with various artificial cracks and delamination's. The authors utilised pulsed infrared thermography and experimented with different angles of pulses to enhance crack measurement. Experiments were conducted using four concrete specimens with same layers of CFRP with two of them having artificial and other two having cracks after loading. A halogen lamp with rated power 2000 W and Vari beam capability and placed at varying distance from the slab was used for thermal excitation. The authors found that pulsed thermography is able to detect location and size of defects accurately. The accuracy of crack detection depends upon distance of heating source and pulse interval.

3.2 Objectives and scope

An extensive literature survey was carried out and it was found that most of the research focussed on identifying and locating the damages. There are commercially available infrared cameras that capture infrared radiation emitted by objects and display it as a thermal image called as a still image thermal camera. High-end cameras, such as recording-type thermal cameras, capture multiple sequences of thermal images and generate a video file containing temperature data. The still image and recording type camera have been used extensively in this study and it is observed that thermal images recorded by camera display only surface temperature values. The presence of high or cold temperature spot in the thermal image is most likely an indication of sub surface defect. However, interpretation of the presence of defect and its area is largely left upto the user operating the camera. The results like area of defect are essential from repair point of view and need to be determined accurately. Hence thermal images captured by infrared camera need to be processed by user to get meaningful results. Therefore, it is necessary to develop a systematic method to estimate the area of defects. Spatial techniques with image enhancement methods were used by Zhao & Chen, (2013) to obtain the area of defects in a retaining wall. The authors concluded that area of sub-surface defects can be calculated by using image processing techniques and programs. However, no clear techniques were presented.

Hence, the experimental program shown in Figure 7 is conceived to conduct infrared thermography and use thermal images for developing a method to calculate defect areas. For the experiment, slab samples were cast with hidden damages at different depths having different sizes. The active infrared thermography is performed on the slab and thermal hotspots are observed. The defect area is calculated utilizing an algorithm implemented in a computer program. The program utilizes surface temperature values and calibration to determine area of sub-surface defects. The calculated area is then compared with actual area of defects and the error percentage is calculated. This program can be automated to select and calculate defect area by identifying desired temperature thresholds. The program can calculate area of defect based on identified temperature threshold. This study was developed with intention to integrate method developed into software of infrared camera. The authors want to develop infrared thermography as a suitable Non-Destructive Testing method for construction industry. The determination of area of defects is essential for deciding type and extent of repair method to be employed. It is found that the program can accurately identify defect area. The accuracy of defect area identification is dependent on quality of thermal image. To verify the computer program, active infrared thermography is simulated on validated FEA model of the slab. The

area of defects identified from thermal images of FEA simulation is successfully calculated using program.

The comparison between experimental and FEA simulation results, shows that many parameters affect defect area identification. An FEA simulation is utilized to investigate these parameters, which simulate real world conditions. The FEA simulations can be utilized to provide useful information about below surface defects as mentioned in the literature survey above. They also help in cases where equipment is not available and avoid time consuming and expensive experimentation. The parameters investigated are the distance of the heating source from slab, the magnitude of thermal excitation, heating duration and the size of defect. It is found that distance of heating source and defect size are the main parameters affecting defect area identification. The detailed methodology and results of current study followed by discussions are explained in subsequent sections.

3.3 Methodology

3.3.1 Casting of concrete slab

The experiment is designed to determine the defect area from thermal images. For this purpose, concrete slab S1 is cast with pre-embedded polystyrene (thermocool) defect. The slab S1 is of size 50 x 50 x 10 cm as shown in Figure 8. A thermocol defect D1 is placed in the slab at time of concreting. Figure 8 shows dimensions of slab S1 and location of D1.

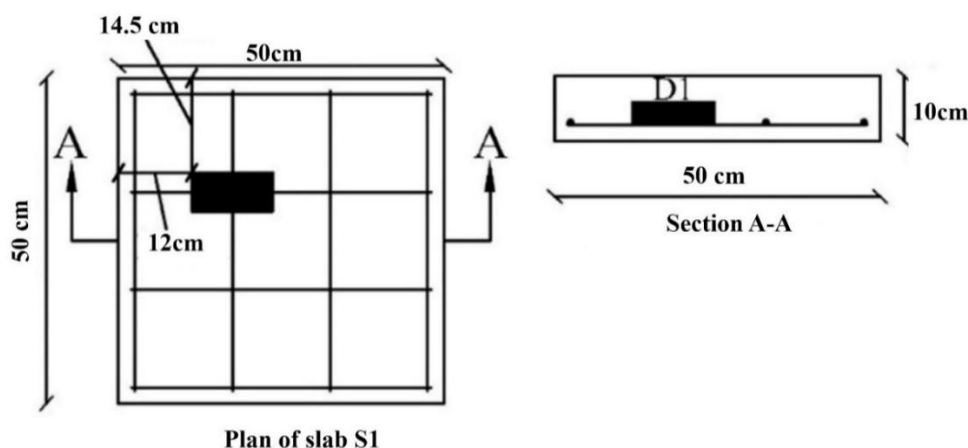


Figure 8 Placement of defect D1

The depth of D1 from the surface is 3.6 cm and dimension is 12.5 x 6.0 x 3.5 cm. Table 1 shows the plan dimension and depth of defect along with width to depth ratio. The width to depth ratio is an important parameter that affects the detectability of defects (*Huh et al., 2018*).

Table 1 Details of defects placed in slab

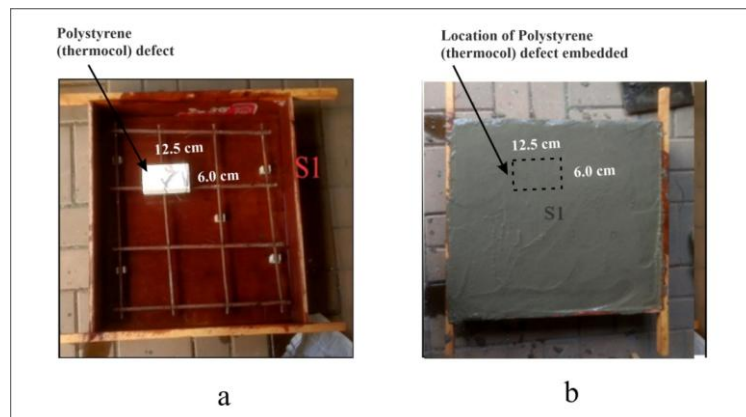
Label	Length (mm)	Width (mm)	Thickness of defect (mm)	Depth from top surface (mm)	Width to Depth Ratio (WTDR)
D1	125	60	35	36	3.47

A mix design is prepared for M25 grade concrete. The required quantity of materials is shown in Table 2. The cement used for mixing concrete is OPC 43 grade cement (JK cement). The steel rebars of JSW TMT make having 8 mm dia. were placed in such a way that they are equally spaced in both directions. The coarse aggregates of size 20 mm and 10 mm were used in ratio of 60:40. The fine aggregate used for mixing concrete is natural river sand.

Table 2 Quantity of materials used for casting the slab

Cement	Water	Coarse Aggregate (20 mm)	Coarse Aggregate (10 mm)	Fine Aggregates
12.5 kg	5.7 L	21.75 kg	14.5 kg	21 kg

The slab is demoulded after 24 hours. The slab is cured by submerging it in curing tank for 28 days as per IS 516:1959. On completion of curing, the slab S1 is subjected to Thermal Non-destructive Testing to detect subsurface defects embedded at the time of concreting. Figure 9 (a) and (b) show the slab before and after concreting.

**Figure 9 a) Placement of rebars and defect D1 b) Slab S1 after concreting**

The defects in form of polystyrene (thermocool) are placed in slab as shown in Figure 9 a. Since polystyrene (thermocool) has thermal conductivity similar to air, it is a suitable material to simulate air void in concrete. Also, polystyrene (thermocool) has been used to simulate embedded defects in concrete in multiple researches *Maierhofer et al. (2003)*, *Hiasa et al. (2017)*, *Cotic et al. (2015)* & *Huh et al. (2018)*.

3.3.2 Active infrared thermography on slab

The stepped infrared thermography is adopted in current study in which, the object is subject to thermal excitation using a continuous heat source. A halogen lamp having rating power 500 W is used as heating source for the experiment. The experimental setup used is shown in Figure 10 a below. The horizontal distance between S1 and Halogen lamp is 1m while the height above the floor is 45 cm. The total duration of thermal excitation is 60 minutes. In the process of thermal excitation, the sequence of images taken are after 5 minutes, 20 minutes, 30 minutes and 60 minutes of thermal excitation. After 60 minutes, thermal excitation of the slab is stopped and an image in cooling phase is taken. A typical thermal image is as shown in Figure 10 b.

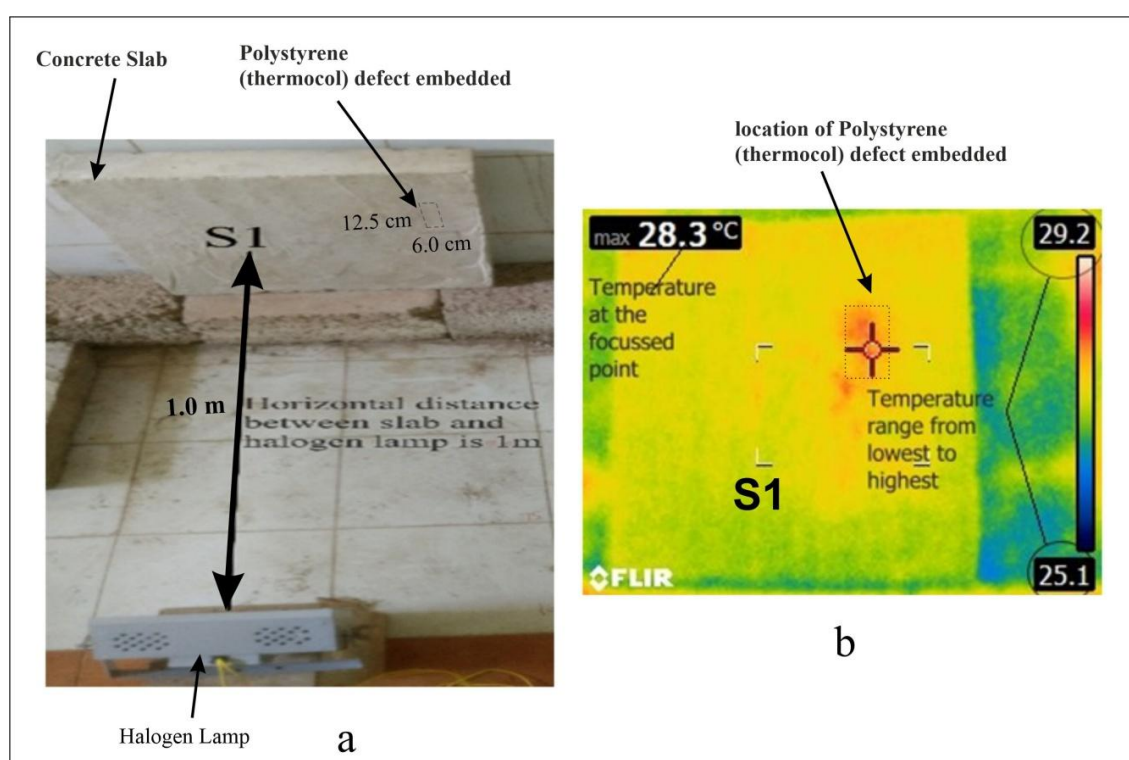


Figure 10 a) Experimental setup b) Typical thermal image

The FLIR E6 hand held thermal camera was utilised for the experiment. The technical specifications of the camera are shown below in Table 3. The thermal hotspot in Figure 10 b appears at the location of the sub-surface defect D1 embedded in slab S1 as shown in Figure 10 a. The thermal camera contains an array of sensors like microbolometers or photodetectors made of InSb (Indium Antimonide), HgCdTe (Mercury Cadmium Telluride). The Stefan Boltzmann law of radiation explained in Section 1.1.1 states that any object having temperature above absolute zero emits infrared radiation. The infrared radiation induces change in electrical properties of the sensors which is converted into electrical signals. Each pixel on the sensor corresponds to a small area on the object. The camera system computes a

temperature value for each pixel by relating the detected IR radiation to surface temperature of object. A thermal matrix containing temperature values is formulated which is converted into pseudo-color images using image processing algorithm. Thermal contours are drawn by connecting points of equal temperature. Color palettes (e.g., ironbow, rainbow, grayscale) are applied to enhance visualization of thermal images. The emissivity correction feature in camera adjusts the temperature range according to the type of object (*Meola et. al, 2004*).

Table 3 Specifications of FLIR E6 thermal imager

Items	Parameters
Temperature measurement range	-20 ⁰ C to +250 ⁰ C (-4 ⁰ F to 482 ⁰ F)
Field of view	45 ⁰ x 34 ⁰
Thermal sensitivity (NETD)	<0.06 ⁰ C (0.11 ⁰ F) / <60 mK
Spatial resolution (IFOV)	5.2 mRad
Image frequency	9 Hz
Detector type	160 x 120
Infrared spectral band	7.5 μ m to 14 μ m
Temperature measurement accuracy	$\pm 2^0$ C or $\pm 2\%$ of reading.

3.3.3 Thermal image processing using computer program

An algorithm is configured to calculate the defect area using the captured thermal images. The program accepts thermal image and calibrates the pixels in the image with actual length units entered by a user. For the calibration process it is necessary to know the plan dimensions of the region of interest. The defect is identified based on temperature variation indicated by color difference in the thermal image. The program thus displays the defect area and histogram of pixels temperature intensities within the identified area. The validation of the algorithm is necessary to establish accuracy of defect area calculation. To conduct this test, various shapes of different areas were drawn on A4-sized paper. The algorithm is run to calculate the areas of different shapes as shown in Figure 11 to verify its accuracy. The area calculated using the algorithm is compared with actual area of shapes. This is shown in Table 4.

Table 4 Results of testing of algorithm to calculate defect area

Shape	Area calculated using algorithm (cm ²)	Actual area (cm ²)	Error (%)
A4 paper (Rectangular)	627.00	629.64	0.42

Rectangle	15.20	15.00	1.33
Circle	27.70	28.28	2.05
Polygon	21.90	22.47	2.54

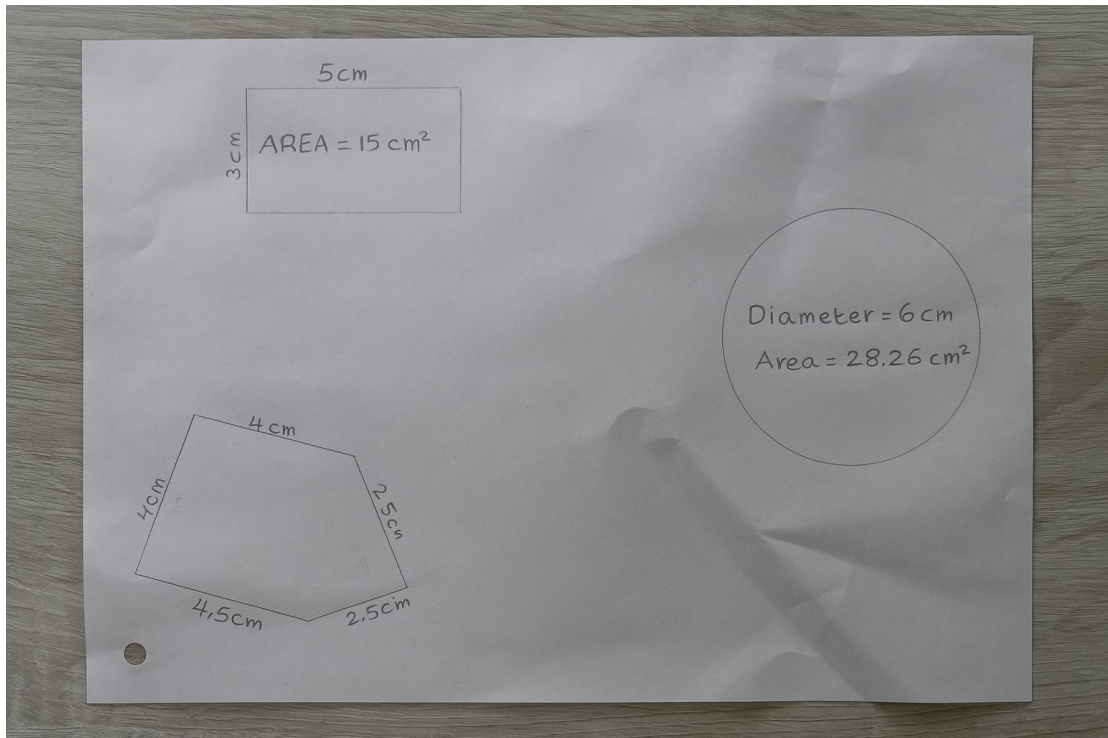


Figure 11 A4 page with different areas for testing of algorithm to calculate defect area

The sequence of operation of the program along with screenshots is shown below from Figure 12 to 15. The first step in the computer program is to perform spatial calibration which is shown in Figure 12. The step involves importing image into the developed program by equating known distance in length units to resolution of image. The resolution of image is defined as number of pixels in horizontal and vertical direction.

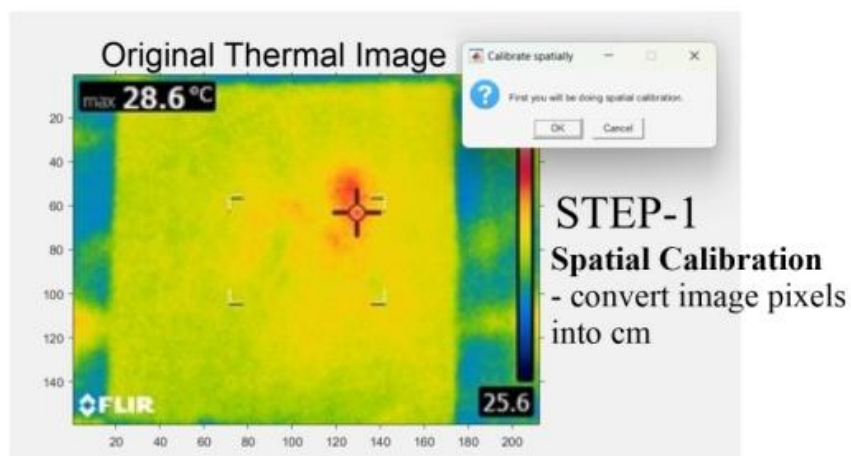


Figure 12 Spatial calibration of image using program

In step 2 the program converts length units into number of pixels per cm as indicated by popup message shown in Figure 13. The spatial calibration step is of utmost importance in the program. The program has been designed with instructions appearing as popup messages to help the user perform calibration accurately. The program gives an option to recalibrate if the user wishes to do again.

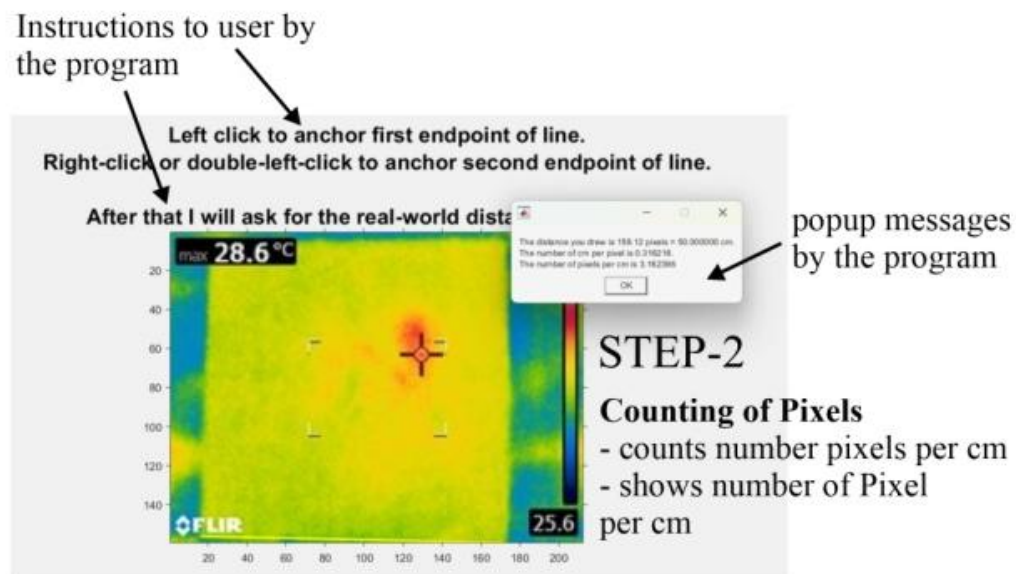


Figure 13 Spatial calibration of image using program

The step 3 in program as shown in Figure 14 provides users with options to measure length, area or recalibrate. The higher temperature region indicates the presence of a defect area which is quantified based upon the temperature. The program is then given a command to calculate the defect area.

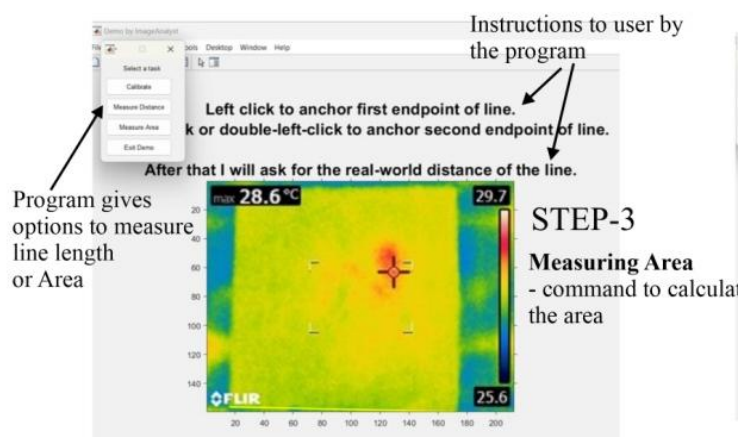


Figure 14 Spatial calibration of image using program

The last step in the program displays the area of defect as shown in Figure 15. The calculated area of defect is then compared with the actual defect area.

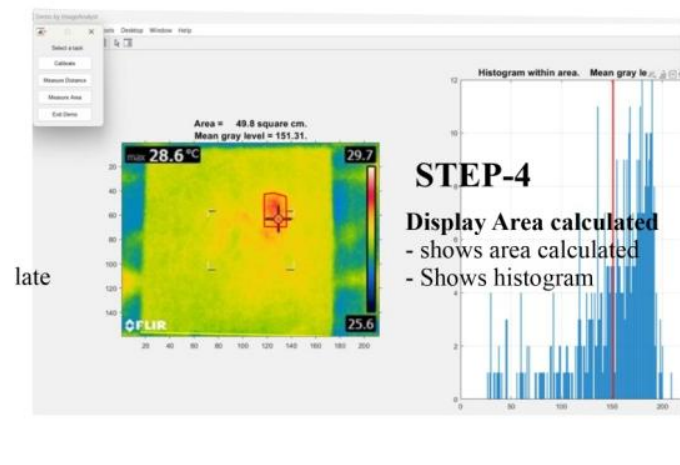


Figure 15 Calculated area of defect is displayed

3.3.4 FEA simulation of experiment

The Finite Element Model of the concrete slab S1 with an inbuilt defect is developed to collaborate with experimental investigations. An FEA simulation of the experiment has been conducted to tide over any unforeseen inconsistencies in the results. There are commercial FEA software packages that can accurately simulate real time thermal effects. Thermal analysis of concrete slab model was done using commercial FEA software ANSYS Workbench. The slab is modelled in FEA software in such a way that it is as close to actual conditions as possible. The size of the slab model is kept the same as experimental dimensions i.e. 50 x 50 x 10 cm. To model the R.C.C. slab 3D cuboid is created. Line bodies in both directions at equal spacing were created to represent reinforcing bars. Figure 16 a shows FEA model of the slab. Thermal images of FEA simulation were captured in the same sequence as that in the experiment. The program is used to calculate area of defect from thermal images obtained from simulation. A typical thermal image obtained from FEA simulation is shown in Figure 16 b.

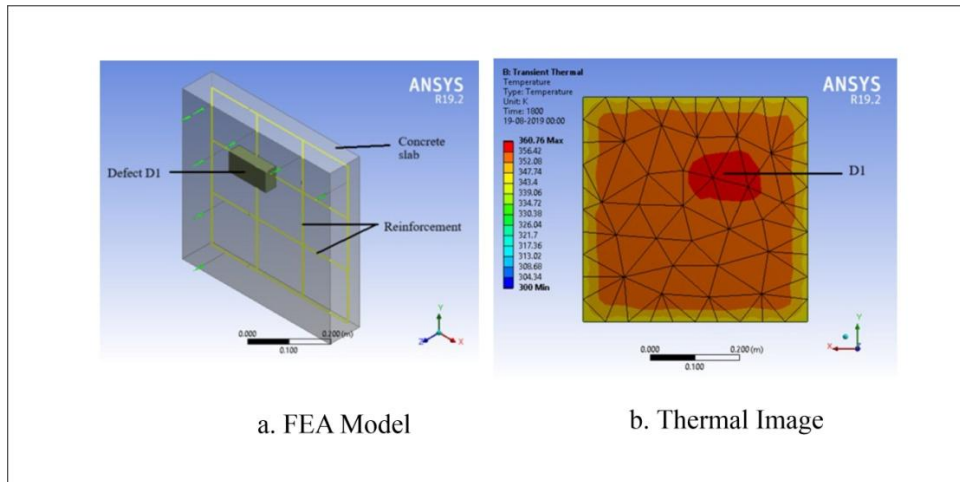


Figure 16 a) FEA model of slab using ANSYS Workbench b) Typical thermal image of slab

The material properties of the cast slab were simulated in FEA model to represent real world conditions. The thermal conductivity of concrete is assigned keeping in mind actual concrete. The thermal conductivity of concrete at different temperatures is shown in Table 5. This is adopted from *Kook-Han et al., (2003)*.

Table 5 Thermal conductivity values of concrete at different temperature

Temperature (K)	Thermal conductivity (W/m-K)
293.15	1.90
295.15	1.88
297.15	1.86
299.15	1.84
301.15	1.80
303.15	1.80

The data from Table 5 is used to generate a plot of thermal conductivity of concrete versus time as shown in Figure 17.

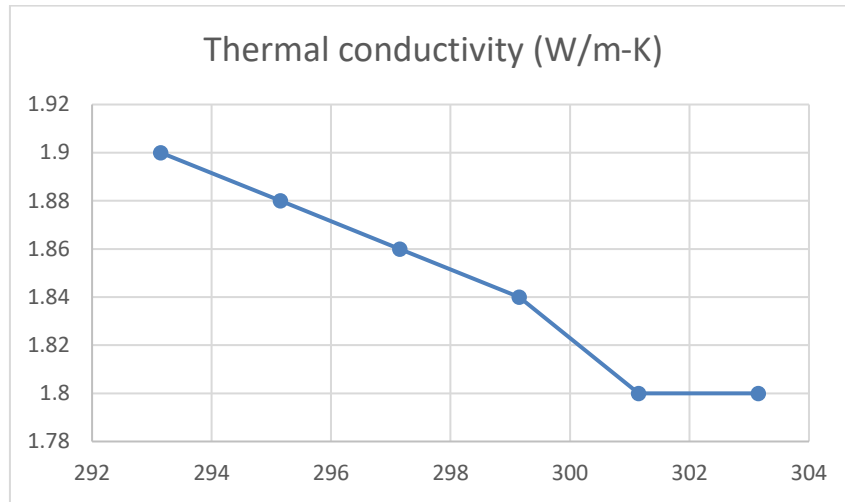


Figure 17 Variation of thermal conductivity of concrete with temperature

The material properties utilised for the model are shown in Table 6.

Table 6 Properties used for the model

Properties	Concrete slab	Reinforcement
Density (kg/m ³)	2500	7850
Elastic modulus (N/m ²)	2.5E10	2.1E11
Strength (N/m ²)	2.5E07	5.0E08
Thermal conductivity (W/m-K)	Table 5	60.5
Specific heat (J/kg-K)	900	434

The bonding between concrete, steel reinforcement and defect in FEA software was adopted. The meshing was done using program-controlled mesh with size as 0.05 m. A mesh size optimisation study is performed to arrive at the optimum mesh size for the FEA model. The model of slab is subjected to heat load of 500 W to simulate halogen lamp adopted for the experimental study. The heat load is applied on the face of concrete where reinforcement was closest. The external natural convection boundary condition is applied on all the faces of the slab except the one where heat load was applied. This boundary condition is considered because flowing air comes in contact with concrete surface and temperature difference between the two causes heat to move away from the surface. The convective heat transfer

coefficient (h) is taken as $12 \text{ W/m}^2\text{-K}$ which is a standard value for concrete as suggested by *Lee et al., (2009)*. The concrete slab is a solid material and does not directly participate in convection. The convective heat transfer coefficient (h) applies to the heat transfer at the concrete surface, where it interacts with a fluid which in this case is air as shown in Figure 1. The thermal images of FEA simulation are recorded in same sequence as that of experiment. The simulation is run in multiple trials till thermal images from the simulation and experiment match. The area of defects from thermal images of FEA simulation is calculated using the program. The results of experiment and simulation are tabulated and compared.

3.3.5 Parametric study using FEA simulation

It is observed that the simulation results display higher surface temperatures as compared to the experiment. Thus, there is a need to investigate the parameters that are affecting the final results. A model of slab and heat source was created as shown in Figure 18 below using COMSOL Multiphysics software. The COMSOL Multiphysics is used for parametric study rather than ANSYS Workbench. This is because of the success of COMSOL Multiphysics to simulate Infrared Thermography as reported by *Cannas et al., (2012)*. The geometrical properties of the model are kept the same as explained in previous section. The slab is subjected to thermal excitation on one edge, however thermal insulation boundary condition is applied on all other edges. The thermal excitation is applied in the form of heat flux with variable intensity. The external natural convection is applied on the surface of slab. This is necessary because air comes in contact with the surface of concrete and due to temperature differences, some of the heat is carried away from the slab surface. Apart from this, surface to ambient radiation and surface to surface radiation boundary conditions are considered to account for heat losses due to radiation. The initial temperature of the slab is assumed to be same as room temperature i.e. 300.15 K . A parametric study is performed by varying magnitude of thermal excitation, duration of thermal excitation, distance of heating source and size of defect.

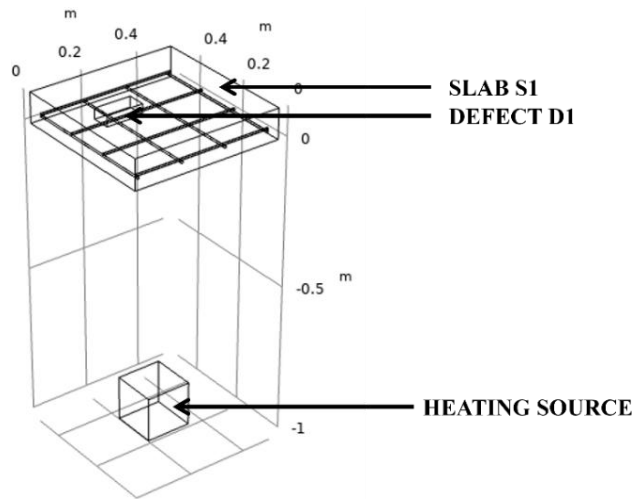


Figure 18 FEM model of slab and heating source in COMSOL

To simulate the defect D1 as an air void in FEA model it is assigned property of air. The material properties of concrete slab and reinforcement utilized for finite element simulation are shown in Table 7. The values shown in Table 7 are standard values for concrete and steel reinforcement and are also present in built-in database of FEA software.

Table 7 Material properties assigned in the model

Properties	Concrete	Reinforcement
Thermal conductivity k [W/m-K]	1.80	44.5
Heat Capacity C_p [J/kg-K]	900	475
Surface emissivity	0.95	NA
Density ρ [kg/m ³]	2500	7850

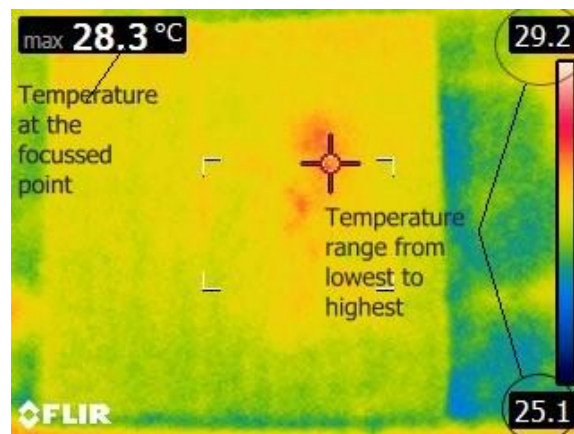
The parametric study is conducted by varying the parameters like distance of heating source, magnitude of thermal excitation, thermal excitation duration and area of damage. The magnitudes of thermal excitation considered are 500W, 1000 W and 2000 W. The distances

of heating source from the concrete slab surface considered in the study are 0.6 m, 0.85 m and 1.35 m. The thermal excitation is turned off after 90 minutes. The thermal excitation duration increases to 180 minutes when the defect area is increased. The program configured in this study calculates defect area observed in thermal images obtained from parametric study. The defect area obtained from program is plotted versus duration of thermal excitation. The results of all the above studies are shown in section 3.4.

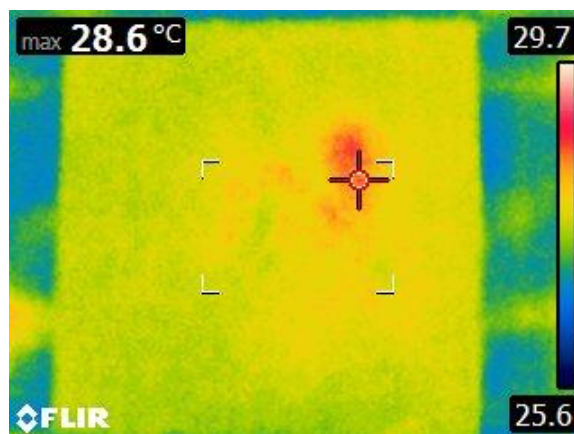
3.4 Results

3.4.1 Active infrared thermography experiment

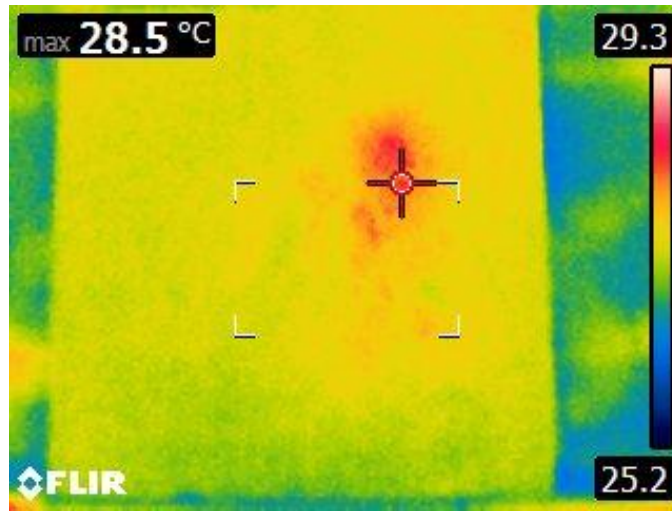
The thermal images are recorded using infrared camera at different stages of thermal excitation as explained in section 3.3.2. The thermal images are recorded after 5 minutes, 20 minutes, 30 minutes and 60 minutes. The sequence of images taken are shown in Figure 19 below. A thermal hotspot appears at the defect location as observed from the thermal images shown in Figure 19. The active infrared thermography identified the presence of hidden defect D1 after 5 minutes of thermal excitation. An infrared camera is used to record the temperature at the hotspot's location. The temperature above the defect location was found to increase with the duration of thermal excitation.



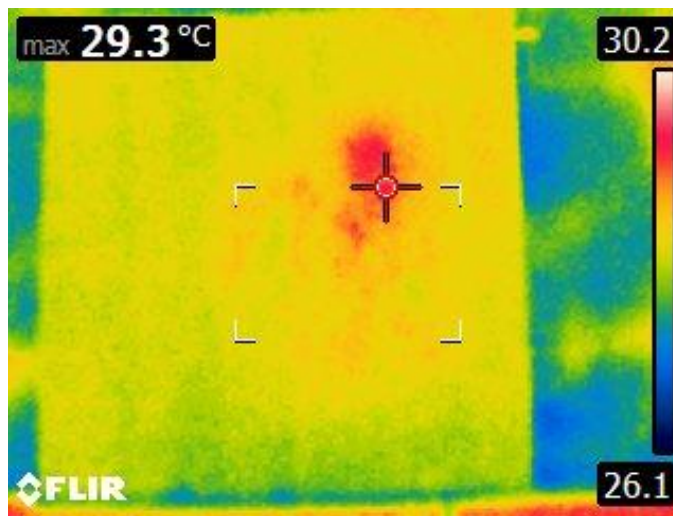
(a) 5 minutes



(b) 20 minutes



(c) 30 minutes



(d) 60 minutes

Figure 19 Thermal images recorded after a) 5 minutes b) 20 minutes c) 30 minutes d) 60 minutes during thermal excitation

The defect area calculated using the program is compared with the actual area of the defect shown in Table 8.

Table 8 Comparison between defect area obtained from experiment and actual defect area

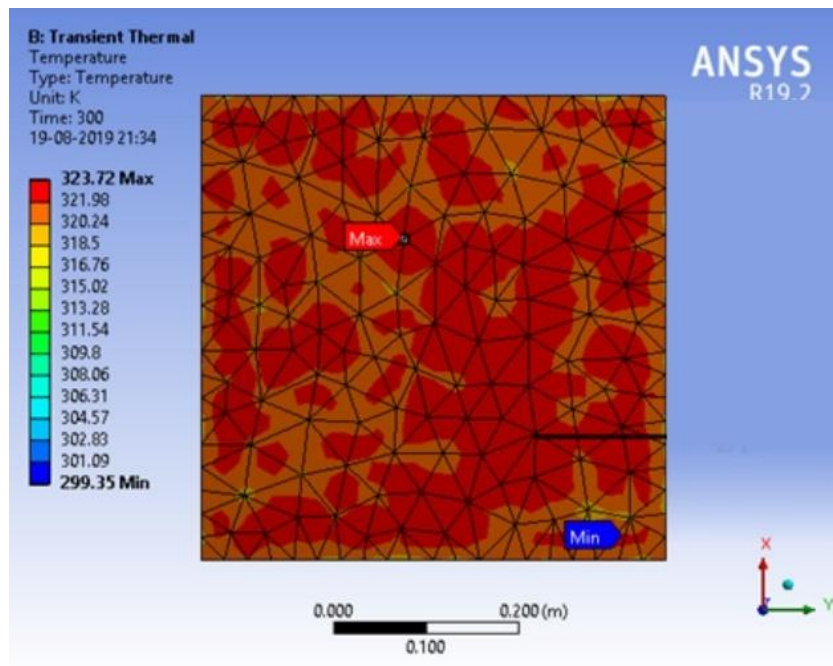
Defect	Dimension (cm x cm)	Heating time / Cooling time	Depth at which D1 is located (cm)	Actual defect area (cm ²)	Defect area using program (cm ²)	Error (%)
D1	12.5 x 6.0	5 minutes	2.0	75.00	35.2	53.1
D1	12.5 x 6.0	20 minutes	2.0	75.00	43.7	41.7
D1	12.5 x 6.0	30 minutes	2.0	75.00	44.8	40.3

D1	12.5 x 6.0	60 minutes	2.0	75.00	50.6	32.5
----	------------	------------	-----	-------	------	------

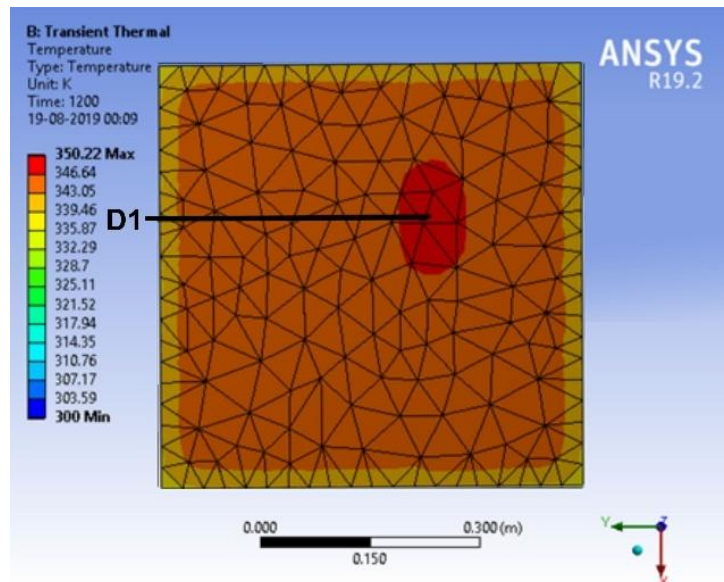
The Table 8 shows that the percentage error between the actual and estimated defect area reduces as the heating time increases. After 60 minutes of thermal excitation, there is a 32.5% error between the calculated and actual defect area. The error between the actual and calculated defect area can result due to factors like variation in ambient temperature, convection currents, reflection from other objects, non-uniform thermal excitation, variation in emissivity, etc. The Table 10 highlights the errors in results obtained from FEA simulation and experiments. The effects of non-uniform thermal excitation and emissivity variation can be minimized by using thermal image post processing methods as mentioned by *Milovanovic et al., (2016)*. The thermal image post processing methods utilised in this study are outlined in Chapter 6. It is decided to simulate the active thermography experiment in FEA software. The simulation replicates the active thermography experiment in ideal conditions to understand how the factors outlined above affect the accuracy of defect detection.

3.4.2 FEA simulation of active infrared thermography experiment

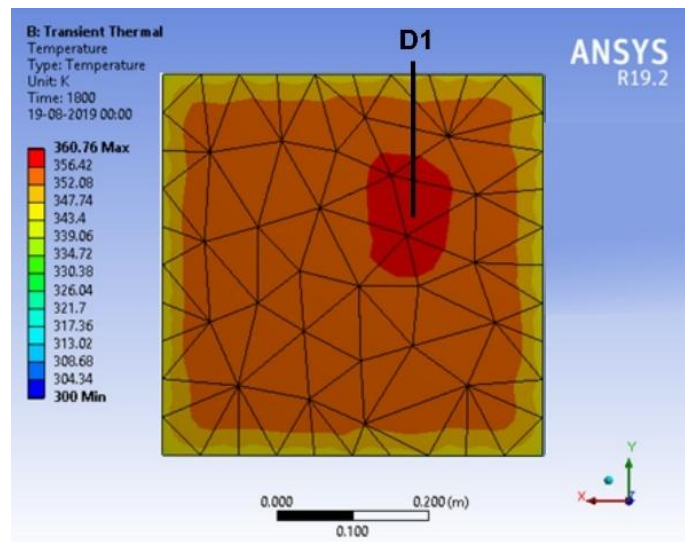
The thermal images of slab surface obtained from FEA simulation are shown in Figure 20. It is observed from Figure 20 a, defect is not visible in thermal image after five minutes of thermal excitation.



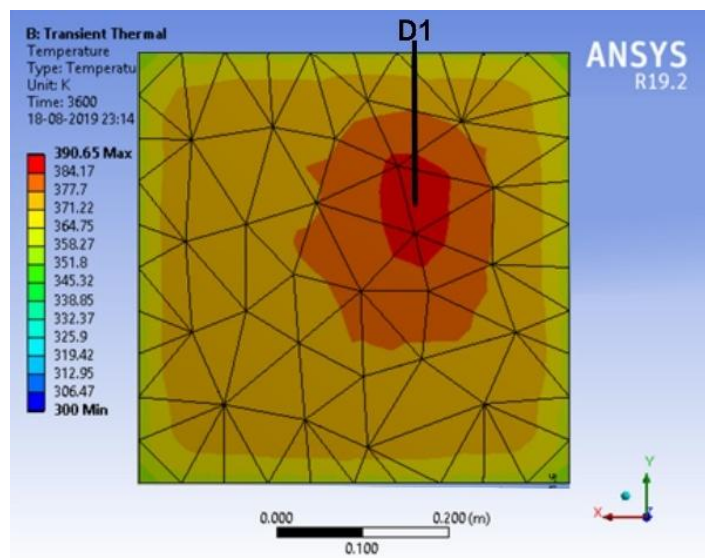
(a) Five minutes heating



(b) Twenty minutes heating



(c) Thirty minutes heating



(d) Sixty minutes heating

Figure 20 Thermal images obtained from FEA simulation recorded at different times during thermal excitation

It is observed from Figure 20 that thermal images obtained from FEA simulation show higher surface temperature compared to experiment. A comparison between surface temperatures of thermal images obtained from the experiment and FEA simulation is shown in Table 9. The differences between simulated and experimental results can be attributed to multiple factors. Infrared thermography relies heavily on accurate emissivity calibration. Table 10 shows the difference in results between FEA simulation and active Infrared Thermography experiment. The concrete is a heterogeneous material, as a result surface emissivity is not uniform. The variations in surface properties or environmental reflections can distort the true temperature field. The FEA model assumes uniform, idealized boundary conditions and material properties, which may not fully capture real-world complexities such as thermal contact resistance or localized convection effects. From Figures 20 a to 20 d it is seen that the simulation thermal images are similar to those observed in the experiment.

Table 9 Comparison of surface temperatures for different heating times

	Experimental (K)	FEA simulation (K)	Difference (K)
5 minutes heating	301.45	322.41	20.96
20 minutes heating	301.65	349.98	48.33
30 minutes heating	301.75	359.34	57.59
60 minutes heating	302.45	388.60	86.15

The program is used to calculate the area of defect from thermal images. The comparison between defect area and actual area obtained from experimental and simulation results is shown in Table 10.

Table 10 Comparison between actual area and defect area obtained from experiment and FEA simulation

Defect	Dimension (cm x cm)	Heating time	Defect depth (cm)	Actual area of defect (cm ²)	Defect area obtained from experiment (cm ²)	Error (%)	Defect area obtained from FEA simulation (cm ²)	Error (%)
D1	12.5x6.0	20 min	3.6	75.0	43.7	41.7	90.9	21.2
D1	12.5x6.0	30 min	3.6	75.0	44.8	40.3	87.8	17.0

D1	12.5x6.0	60 min	3.6	75.0	50.6	32.5	84.7	12.9
----	----------	--------	-----	------	------	------	------	------

The Table 10 shows that the error in the calculated area is less for the FEA simulation compared to the experiment. This is due to a large amount of heat loss and the effect of atmospheric conditions on experimental results. From this simulation it is understood that various factors affect the accuracy of damage area identification. Hence parametric study is devised to be conducted using FEA simulation. The results of the parametric study have been shown in section 3.4.3.

3.4.3 Parametric study

The results of the parametric study as explained in section 3.3.5 have been summarized in this section. The magnitudes of thermal excitation considered are 500W, 1000 W and 2000 W. The distances of heating source considered are 0.6 m, 0.85 m and 1.35 m. The standard thermal excitation duration is 90 minutes. This duration is increased to 180 minutes when the defect is larger. The program computed the defect area for three different parameter variations, and these calculated areas were compared with the actual defect areas. The comparison is presented in Table 11.

Table 11 Comparison of defect areas obtained from parametric study

Distance of source	0.60 m		0.85 m		1.35 m	
Heating duration (min)	Actual area (cm ²)	Area from program (cm ²)	Actual area (cm ²)	Area from program (cm ²)	Actual area (cm ²)	Area from program (cm ²)
10	75	Not visible	75	Not visible	75	Not visible
20	75	Not fully formed	75	Not fully formed	75	Not fully formed
30	75	Not fully formed	75	45.8	75	44.9

45	75	90.7	75	50.9	75	44.6
60	75	85.2	75	52.2	75	45
75	75	81.9	75	55.3	75	48.8
90	75	77.5	75	54.8	75	50.1

The results of parametric study were plotted in form of bubble graphs shown in Figures 21 to 26. In these plots the area obtained using the program is plotted versus heating duration. The red bubbles show area of defect identified for heat source located at distance of 0.6 m from slab, yellow bubbles show area of defect identified for heat source located at distance of 0.85 m from slab and pink bubbles show identified for heat source located at distance of 1.35 m from slab. The numbers on the right of each graph indicate defect area calculated using program in cm^2 . Figures 21 to 23 show variation of calculated area with heating duration for defect occupying 3% of slab area.

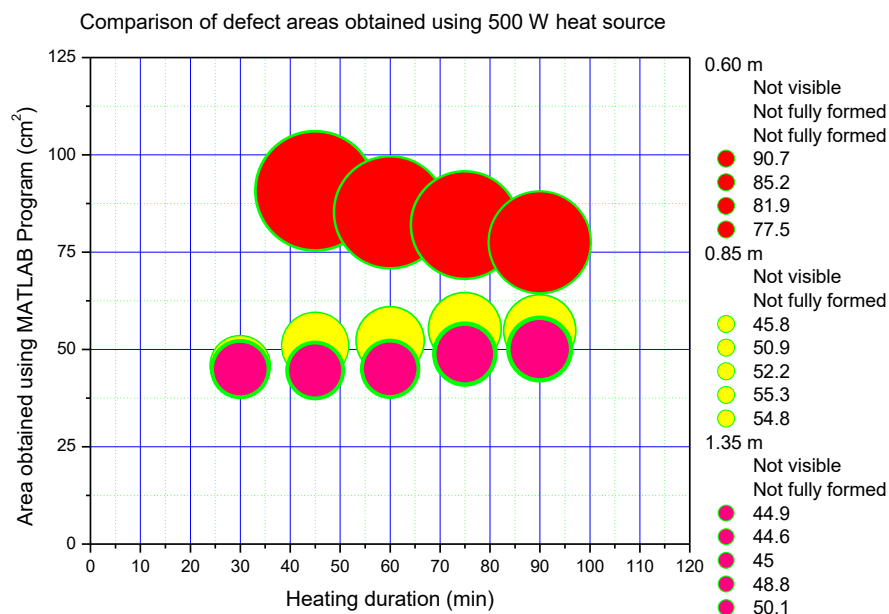


Figure 21 Plot showing variation of defect area obtained using 500 W source

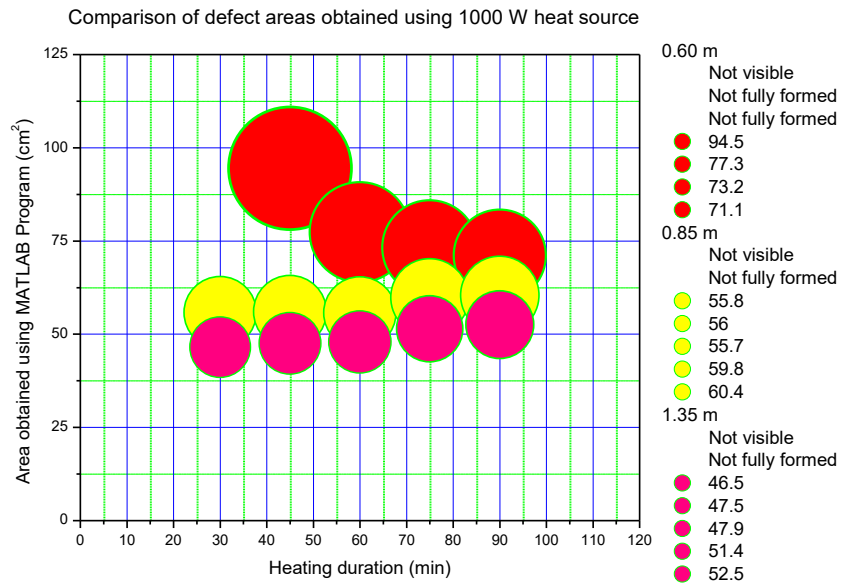


Figure 22 Plot showing variation of defect area obtained using 1000 W source

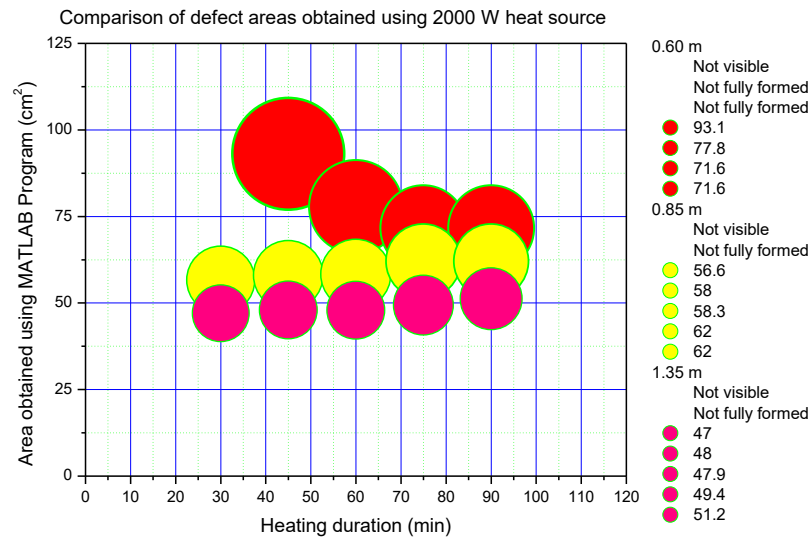


Figure 23 Plot showing variation of defect area obtained using 2000 W source

It is observed from Figure 21 and 22 that minimum 30 minutes of thermal excitation is required for defects to be visible in thermal images when the heating source is located at a distance of 0.8 m and 1.35 m. The duration increases to 45 minutes when the source is located at a distance of 0.6 m as seen in Figure 23. This is because of the concentration of radiation from the heat source at a small slab area due to it being very close to the surface. Additionally, the percentage error between the calculated defect area and the actual defect area reduces as the heating duration increases. The program's calculated defect area is closer to the actual defect area when the source is at 0.60 m. From Figure 21 to 23 it is observed that the magnitude of thermal excitation was found to have minimal influence on the defect area identification.

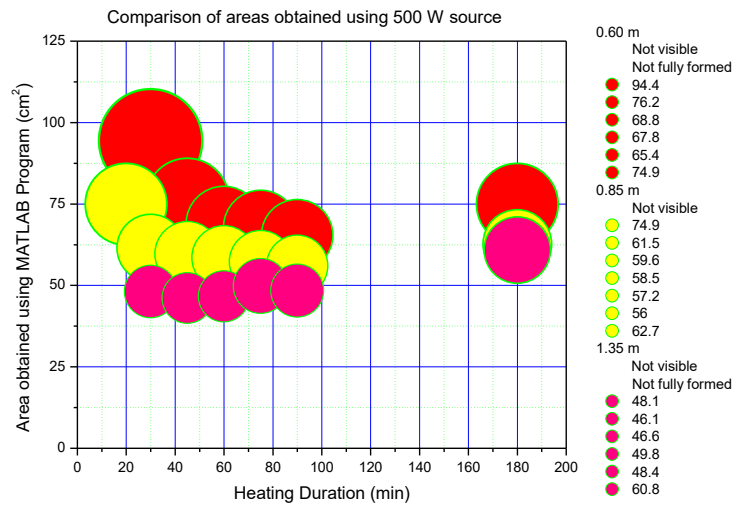


Figure 24 Plot showing variation of defect area obtained using 500 W source

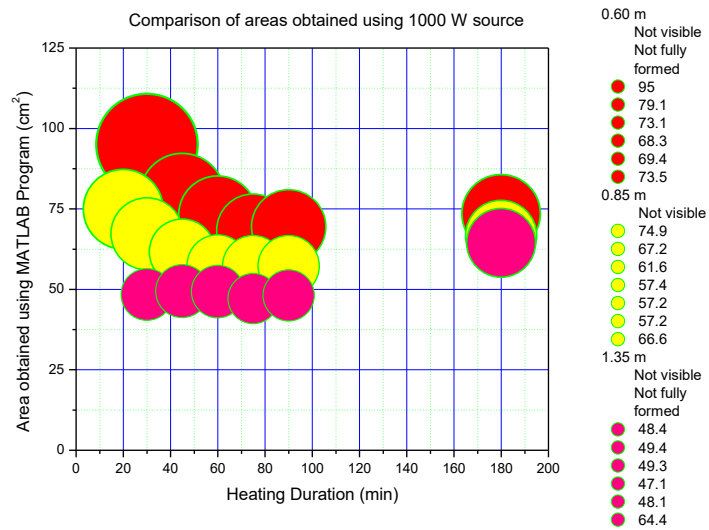


Figure 25 Comparison of defect areas obtained using 1000 W source

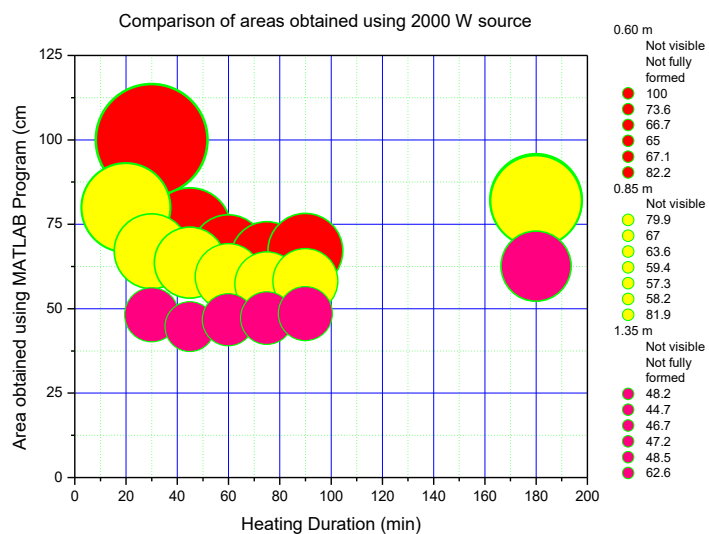


Figure 26 Comparison of defect areas obtained using 2000 W source

In Figures 24 to 26, the actual defect area is increased to 125 cm². The graphs display a decreasing trend for all the distances of the heating source from the slab. The percentage error remains high after 90 minutes of thermal excitation, therefore, the duration was extended to 180 minutes.

3.5 Observations

The error between the defect area calculated using the program and the actual defect area was observed to decrease with increasing thermal excitation duration. This trend is corroborated by the results summarized in Tables 8, 10, and 11. A comparative analysis between the experimental results and FEA simulations demonstrates that active infrared thermography can be effectively simulated using FEA software to achieve accurate results. However, experimental outcomes are influenced by several factors, necessitating a parametric study to investigate the parameters affecting defect area identification.

The results of this parametric study are presented through bubble plots in Figures 21 to 26, where the defect area estimated by the program is plotted against the heating duration. The color coding of the bubbles represents the distance of the heat source from the slab surface:

- Red bubbles: 0.6 m
- Yellow bubbles: 0.85 m
- Pink bubbles: 1.35 m

The numerical values adjacent to each bubble indicate the defect area (cm²) determined from the thermal images processed using the developed program.

- Figures 21 to 23 correspond to simulations where the defect occupies 3% of the slab surface area.
- Figures 24 to 26 correspond to simulations with a defect occupying 5% of the slab surface area.

As illustrated in Figures 21 and 22, a minimum of 30 minutes of thermal excitation is required for the defect to become visible in thermal images when the heat source is positioned at distances of 0.85 m or 1.35 m from the slab surface. In contrast, when the heat source is placed at a closer distance of 0.60 m, a minimum of 45 minutes of thermal excitation is necessary for defect visibility. This behavior is attributed to the concentration of thermal radiation over a smaller slab area when the source is close, which leads to non-uniform heating and delayed defect identification.

Furthermore, the results in Figures 21 to 23 reveal that the percentage error between the program-derived defect area and the actual defect area diminishes with increased heating duration.

In the case of larger defects occupying 5% of the slab area, as shown in Figures 24 to 26, a significant difference between the actual defect area and the calculated area was noted at 90 minutes of thermal excitation. However, this discrepancy was substantially reduced when the excitation duration was extended to 180 minutes. Additionally, it was observed that increasing the distance of the heating source from the slab surface leads to a larger deviation between the actual and calculated defect areas.

The FEA simulation of the concrete slab subjected to thermal excitation accurately replicated the heat flow and temperature profiles within the slab. The simulation effectively identified defects by capturing the higher temperatures over defect regions. The thermal images generated from the FEA simulations were further analyzed using the developed program to compute the defect areas. The findings indicate that increasing the magnitude and duration of thermal excitation enhances the accuracy of defect area estimation.

However, positioning the heating source too close to the concrete surface was found to cause non-uniform heating, resulting in a delay in defect detection. A key advantage of FEA simulation is its ability to reduce the reliance on costly and time-consuming experimental procedures. Simulations can be employed to determine the optimal thermal excitation parameters, such as duration and distance, necessary for accurate subsurface defect detection before field application. Additionally, FEA simulations can help in estimation of the optimal thermal contrast between defective and sound areas.

Nonetheless, the FEA simulation results must be validated against experimental data to ensure the accuracy and reliability of predictions. The findings and methodologies discussed in this chapter are previously documented in publications by *Naik et al.* (2020; 2021).

Chapter 4

FE simulation technique (Indirect method) to obtain defect depth

4.1 Outline of study

The Figure 27 below shows a flowchart depicting the methodology to develop indirect method to obtain defect depth outlined in this chapter.

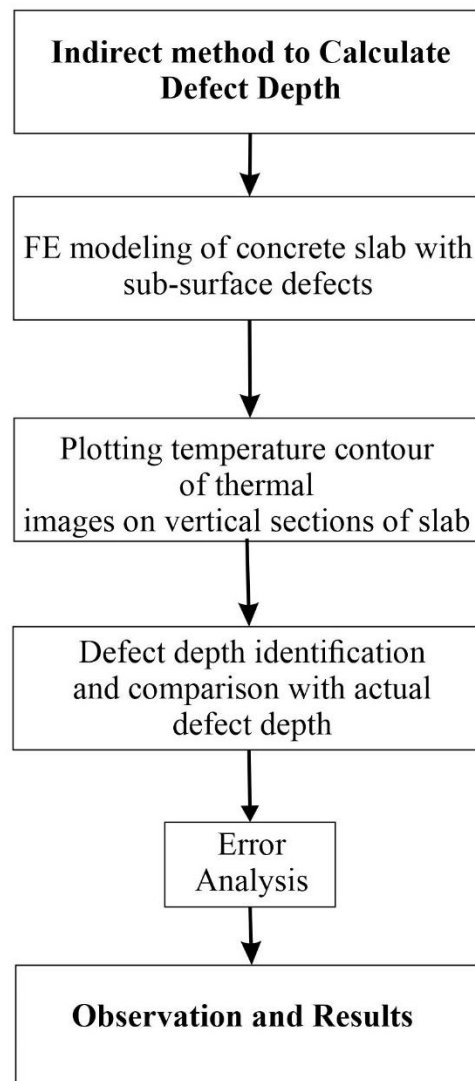


Figure 27 A flowchart of methodology to develop indirect method to calculate defect depth

4.2 Objectives and scope

In chapter 3 the stepped infrared thermography technique is utilised to identify defects embedded inside concrete slab. The importance of understanding percentage of defect area while doing strength and repair evaluation is understood, hence program is configured to calculate the area of subsurface defects from thermal images. It is seen that FEA simulations

can be used to recreate the experiments along with all external factors affecting it. Many researchers have used FEA models to simulate infrared thermography inspections. Some of the research publications are referenced here. FEA simulations were used to develop a methodology to interpret and detect delaminations in bridges from IR images because of difficulty in identifying just from color contrast. Temperature of sound part was obtained from experiment while temperature of defect area was obtained from FEA simulation. The defects were identified easily by this method but results were affected by boundary conditions and time of data collection as mentioned by *Hiasa et al., (2017)*. Infrared camera along with matrix of heat sensors was used to determine heat distribution and heat capacity on surface of laboratory cast concrete slab. FEA simulation of experiment was used to find out influence of embedded steel bars on thermal response. FEA simulation can be used to provide useful information about effect of embedded materials on heat transfer in slab as studied by *Gabriel et al., (2015)*. FEA simulations were used along with Infrared Thermography to explore favourable time windows for bridge deck inspection. It is concluded that optimal condition for damage detection was night time under clear sky condition. Obstacles did not have much effect on results and could be easily distinguished (*Hiasa et al., 2018*). The FE models of concrete slabs with artificial delamination's can be used for more accurate and reliable processing of data by defining criteria for thermal contrast (*Hiasa et al., 2018*). Infrared Thermography on concrete slab with inbuilt defects was simulated in FEA software and subjected to time varying thermal excitation. The depth of the defect was determined by taking vertical sections and plotting temperature contours. The depth of defects with different thicknesses could be determined with up to 2% error (*Naik et al., 2022*).

The papers referred above show that FEA simulations can be utilised to model exact conditions as in experiment. Hence a pseudo experiment of thermal imaging is conducted on concrete surface using FEA simulations. A concrete slab model having defects inbuilt of known thicknesses and at known depths from the surface is used. The surface of slab is subjected to thermal excitation of fixed frequency over time. This is called lock in thermography. Vertical sections are taken across depth of slab and temperature contours were plotted. The temperature contour on vertical sections passing through the defects is used to determine the depth of damage. It is found that with this technique depth of defect could be determined with error up to 2% of actual depth. The results of simulation study are reported. It is demonstrated that the technique of plotting thermal contour can be very well be utilized to determine the depth of defect. The objective behind developing this indirect method is to accurately determine the depth of defects. The determination of depth of defect is essential to decide type of repair

method to be adopted. The detailed methodology adopted to obtain results of this study is explained in section 4.3.

4.3 Methodology

4.3.1 FEA simulation

The simulation study involves modelling a concrete slab of dimension 1 m x 1 m x 0.3 m as shown in Figure 28. The material properties assigned to the model are summarized in Table 12. The defects of known size and depths were embedded in the slab. A linear elastic constitutive model was used to represent Plain Cement Concrete (P.C.C.) slab concrete in this study. The slab is discretized using free triangular 3D elements by adopting meshing methods. The discretization is done in such a way that finer elements are near the defects to ensure thermal excitation is more effective in heat conduction near defect region. A mesh sensitivity analysis is performed and it is found that stable results were obtained with mesh sizes ranging from 2 cm to 15 cm. The maximum size of the mesh adopted was 15 cm and minimum size of 2.8 cm was adopted for discretization. The FEM model consists of 11008 domain elements, 1706 boundary elements and 349 edge elements. The adaptive mesh refinement strategy is adopted. In this type of meshing, smaller element size is adopted over the defect region. The software automatically handles the mesh refinement process, reducing user intervention. This process can be repeated iteratively until the desired level of accuracy is achieved.

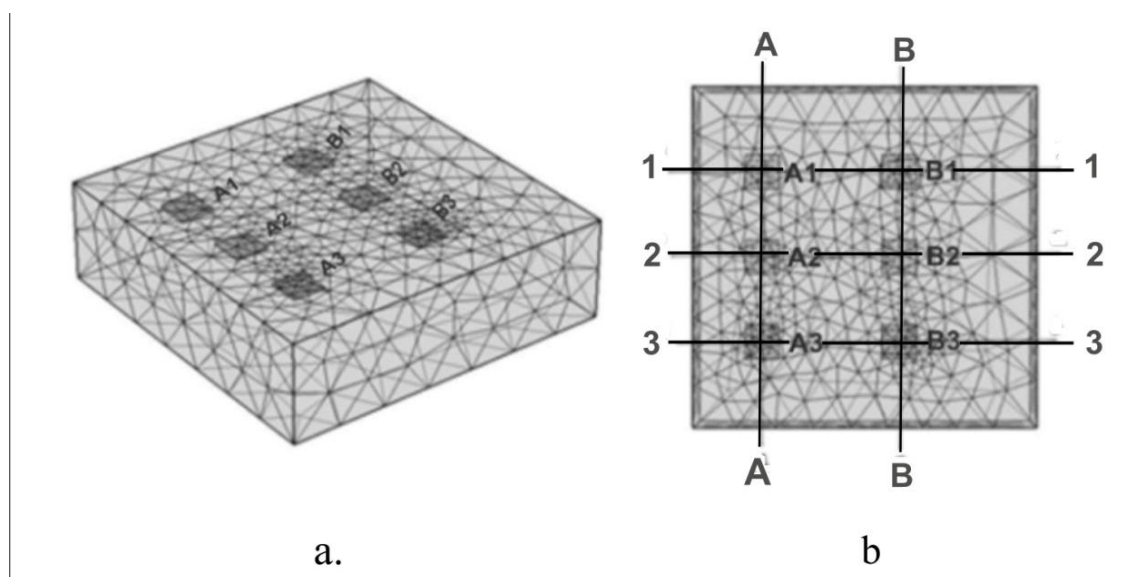


Figure 28 (a) 3D view of discretized FEM model with inbuilt defects (b) Plan view of defects with gridlines

To simulate damage in the slab six rectangular defects are incorporated in slab at known depths from the surface with properties of air void as shown in Figure 28. The details of the size of

defect and their depths from the surface of slab is summarized in Table 12. The defects along grid line AA are located 30 mm below the surface while defects along grid line BB are located 20 mm below the surface. The plan view of the defects is shown in Figure 28 (b).

Table 12 Details of defects

Label	Length (mm)	Width (mm)	Thickness of defect (mm)	Depth from top surface (mm)	Location (x,y) (mm)
A1	100	100	10	30	(150,700)
A2	100	100	5	30	(150,450)
A3	100	100	2	30	(150,200)
B1	100	100	10	20	(550,700)
B2	100	100	5	20	(550,450)
B3	100	100	2	20	(550,200)

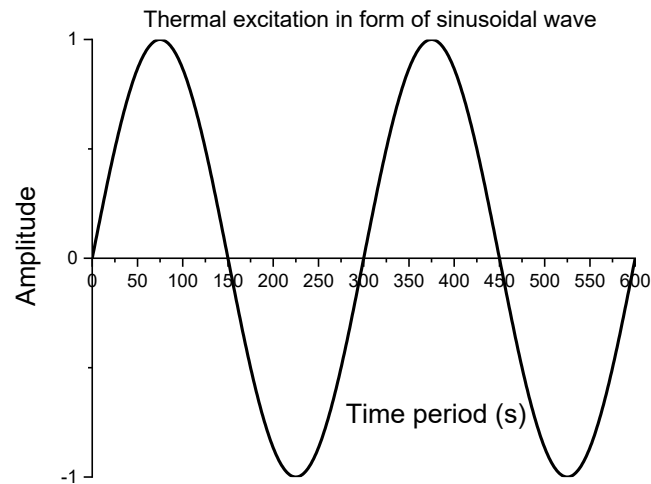
The concrete material property is assigned to the block and air property is assigned to the defects. The details of properties assigned to the FEA simulation is shown in Table 13. The properties for concrete vary with the grade of concrete. The grade of concrete used in this study is M25 and room temperature was 293.15 K. The properties of air vary with atmospheric temperature and pressure as reported by *Caroll et al., (1968)*. Since air is a fluid and not a solid, it does not have modulus of elasticity.

Table 13 Details of material property used in FEM model for simulation of Lock-in Thermography

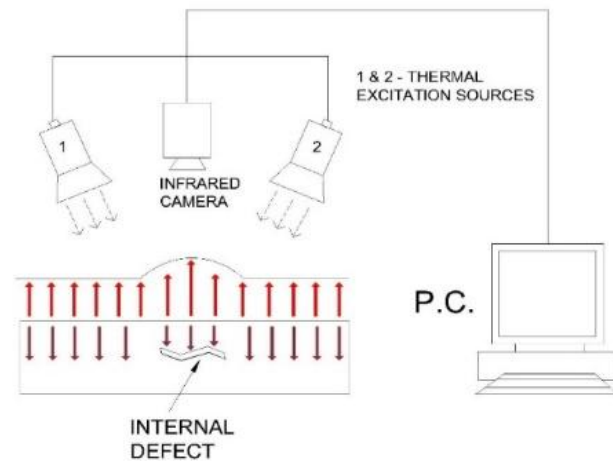
Property	Concrete	Air
Density	2500 kg/m ³	1.204 – 1.225 kg/m ³
Thermal conductivity	1.9 W/m-K	0.0257 – 0.0263 W/m-K
Heat capacity	900 J/kg-K	1005 J/kg-K
Young's modulus	25E09 Pa	<i>Not defined</i> (air is a fluid, not a solid)
Coefficient of thermal expansion	10E-06 1/K	3.4×10^{-3} 1/K

4.3.2 FE simulation of Lock-in Thermography

The lock-in active infrared thermography experiment is simulated in FEA simulation. The surface of the slab is subjected to thermal excitation using heat flux as shown in Figure 29 (a). The typical setup for a lock in thermography experiment is shown in Fig 29 (b).



a) Thermal excitation in form of sinusoidal heat wave. The heat wave is having time period of 5 min



b) Typical setup for Lock-in thermography experiment (Chatterjee, 2011)

Figure 29 Lock in Infrared Thermography using sinusoidal wave for thermal excitation of concrete slab

The magnitude of thermal excitation applied to surface of slab is described by Equation 6. This depends on the intensity of thermal excitation and time period. Heat flux in the form of a

sinusoidal thermal wave is applied onto concrete surface. The magnitude of the heat flux is given by Equation 7:

$$Excitation = p_{source} \times wv1 \left(\frac{t}{period} \right) \quad (6)$$

$$Flux = Excitation / (w_1 \times d_1) \quad (7)$$

Where w_1 and d_1 are the plan dimensions of the slab, $wv1$ is sinusoidal waveform, p_{source} is thermal excitation power and period is time period of sinusoidal waveform. The values of p_{source} which have been considered are 1000 W and 2000 W. Four different time periods for each value of p_{source} is considered i.e. 3 minutes, 5 minutes, 7 minutes and 10 minutes. The total duration of thermal excitation for the slab is 60 minutes. The initial temperature of the slab is taken as ambient temperature of 300.15 K. The effect of emissivity and natural convection is also assigned on the slab.

A pseudo experiment of Lock-in Thermography is conducted on the slab using controlled thermal excitation of varying amplitude and frequency. A time dependent study is conducted on the FEA simulation. In time dependent study, it is possible to obtain thermal images at required time intervals. The thermal images of concrete surface are obtained at every minute of thermal excitation which is used to locate the embedded defects. A typical thermal image of the slab surface obtained using simulation is shown in Figure 30 below.

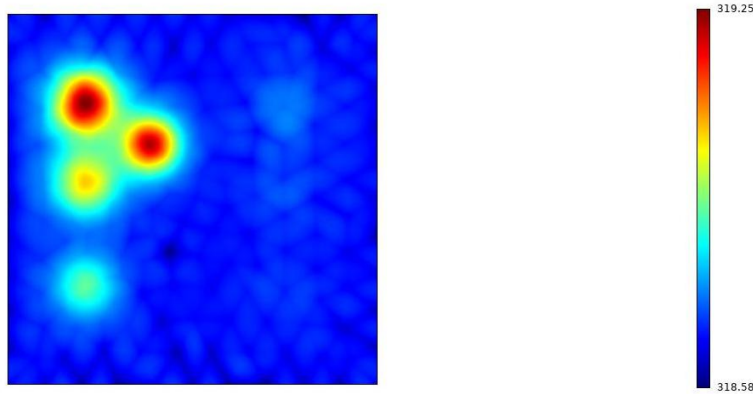


Figure 30 Thermal image of the slab surface obtained from simulation

The thermal images can only provide location and extent of the damage but fail to indicate at what depth those defects are located. The indirect method to accurately calculate defect depth in concrete is developed. This method involves taking vertical sections across the depth of the slab as shown in Figure 31.

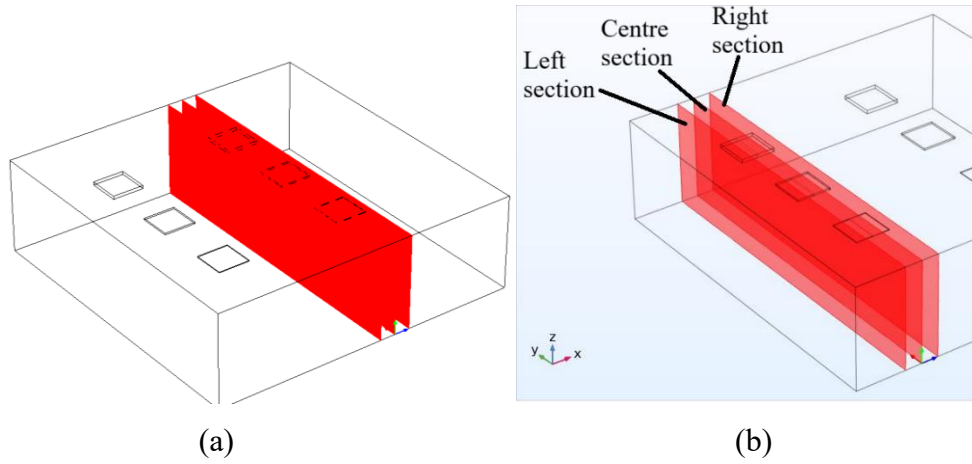


Figure 31 a) Vertical sections across the depth of slab b) Cross section cutting defect location at three places

The temperature distribution data on the three sections shown in Figure 30 b is extracted. This data is plotted in the form of temperature contour as shown in Figure 32.

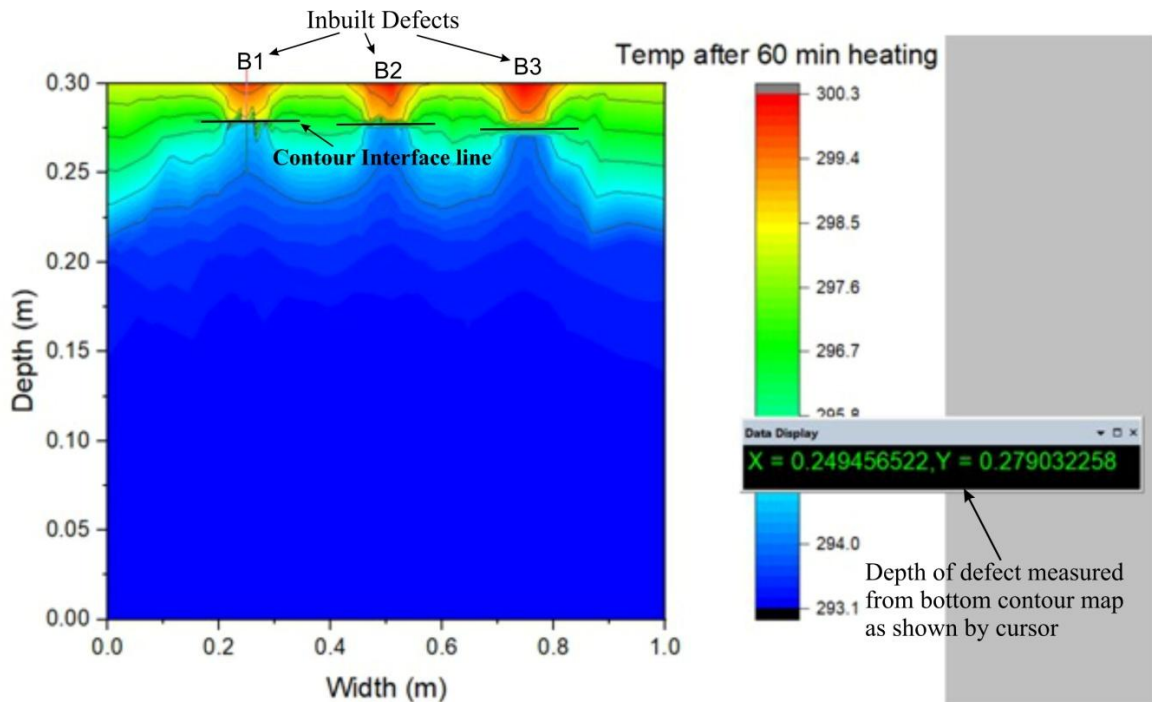
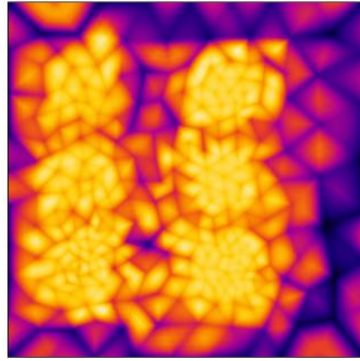


Figure 32 Typical temperature contour on vertical section at location of defects.

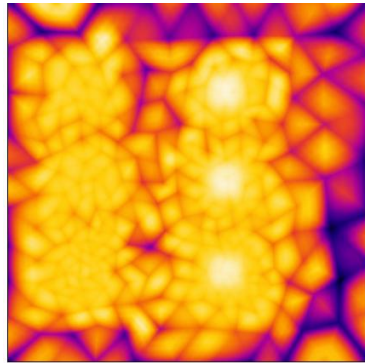
It is observed from Figure 32 that contour lines at the location of defects change from a downward slope to an upward slope after some height. The contour plots of thermal image of cross section showed an increase in temperature upto some depth and later decreased. An interface is drawn where contour line changes slope to zero as shown in Figure 32. The vertical distance from interface to surface is identified as depth of defect. The depths measured are compared with actual defect depths.

4.4 Results

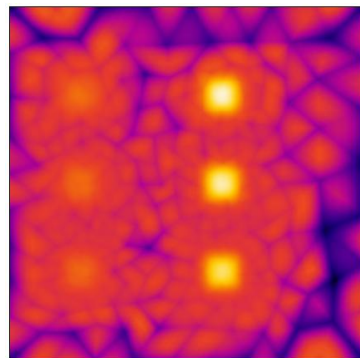
The images of the surface of slab are taken at various times known as thermograms or simply thermal images. The thermograms recorded for a wave having time period 5 minutes and amplitude 500 W designated as wave type I is shown below in Figure 33. Total duration of thermal excitation was 60 minutes.



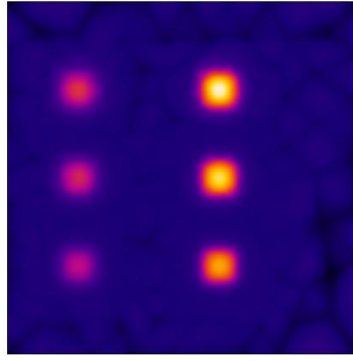
(a)



(b)



(c)



(d)

Figure 33 Thermograms at a) 2.5 minutes b) 7.5 minutes c) 17.5 minutes d) 60 minutes

It is observed from above thermal images that defects at 20 mm depth from surface first appear after 7.5 minutes while defects at 30 mm depth appear at 17.5 minutes after thermal excitation is commenced. The surface temperature distribution of the slab at 60 minutes was plotted in form of 3D graph as shown in Figure 34.

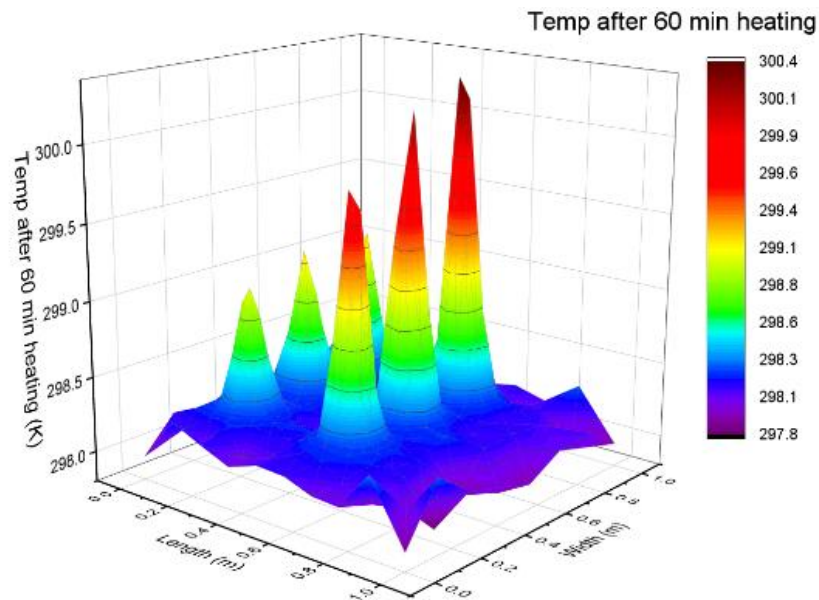


Figure 34 Surface temperature variation after 60 minutes thermal excitation

From above graph it is seen that surface temperature shows a peak at the location of defect. This graph confirms the location of defects which are identified from thermal images. The temperature variation along the vertical sections is plotted in form of contour as shown in Figure 32. At the interface of temperature contour vertical distance was measured and recorded as depth of defect from surface. The obtained depth is compared with actual depth of defect from surface. This is shown in Table 14 and 15.

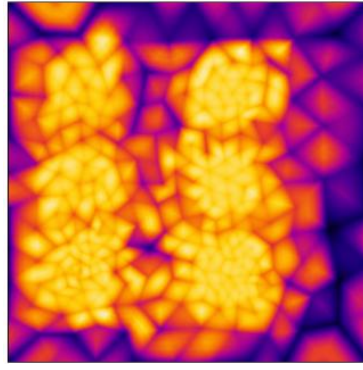
**Table 14 Comparison between actual and measured values of depth for defects located
20 mm from surface of wave type I**

Thickness of defect	2 mm	5 mm	10 mm
Left	0.278	0.277	0.275
Centre	0.279	0.276	0.274
Right	0.277	0.277	0.275
Average	0.278	0.277	0.275
Actual depth	0.28	0.28	0.28
Error %	0.71	1.19	1.90

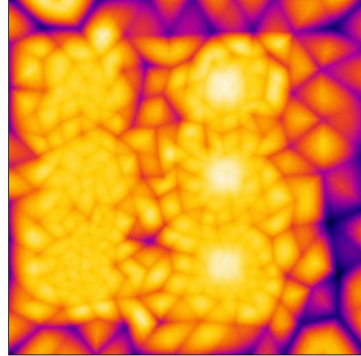
**Table 15 Comparison between actual and measured values of depth for defects located
30 mm from surface of wave type I**

Thickness of defect	2 mm	5 mm	10 mm
Left	0.268	0.267	0.264
Centre	0.269	0.268	0.264
Right	0.265	0.263	0.264
Average	0.267	0.266	0.264
Actual depth	0.27	0.27	0.27
Error %	0.99	1.48	2.22

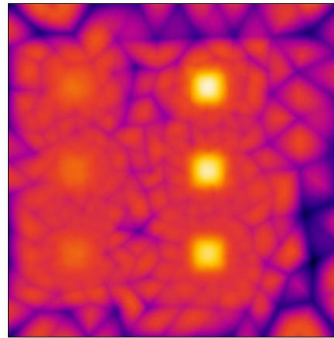
The results shown below are for slab subjected to thermal excitation in form of sinusoidal wave having time period 10 minutes and amplitude 500 W designated as wave type II. The thermograms taken at various times are shown in Figure 35. It is observed that thermal images display same results as wave type I.



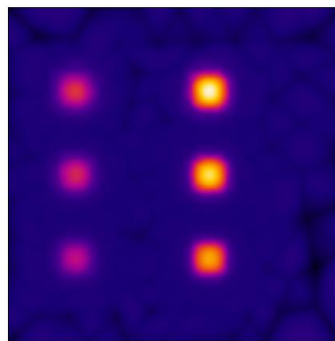
(a)



(b)



(c)



(d)

Figure 35 Thermograms at a) 2.5 minutes b) 7.5 minutes c) 17.5 minutes d) 60 minutes

The surface temperature distribution is shown in Figure 36. Higher surface temperature is observed over defects which are at depth of 20 mm from surface. The same temperature distribution as observed in Figure 34 is seen in Figure 36.

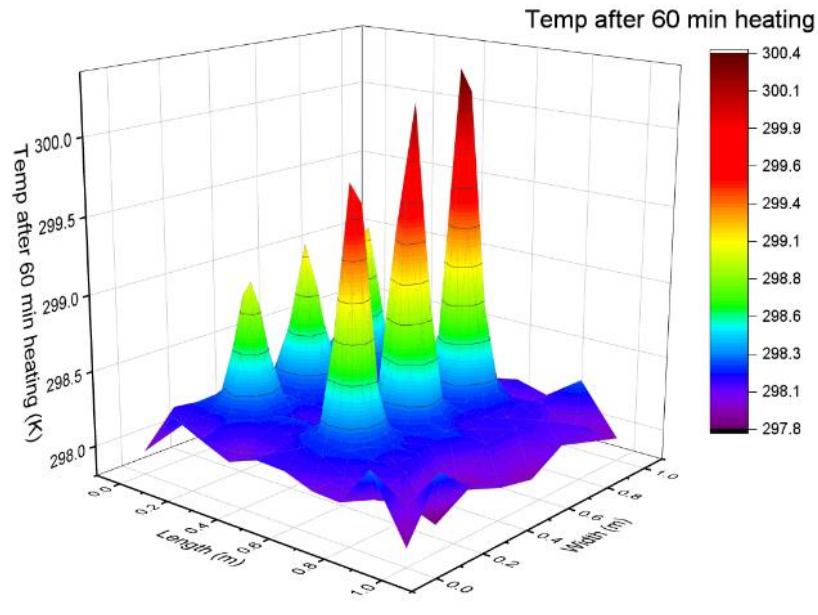


Figure 36 Surface temperature variation after 60 minutes thermal excitation

Defect depth obtained using wave type II is shown in Table 16 and 17.

Table 16 Comparison between actual and measured values of depth for defects located 20 mm from surface of wave type II

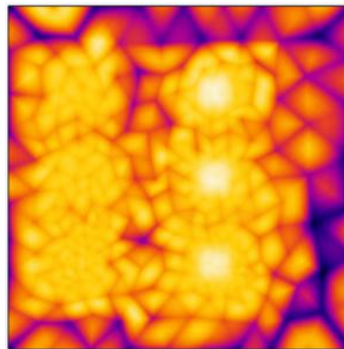
Thickness of defect	2 mm	5 mm	10 mm
Left	0.278	0.277	0.275
Centre	0.279	0.276	0.273
Right	0.276	0.277	0.275
Average	0.278	0.277	0.274
Actual depth	0.280	0.280	0.280
Error %	0.83	1.19	2.02

Table 17 Comparison between actual and measured values of depth for defects located 30 mm from surface of wave type II

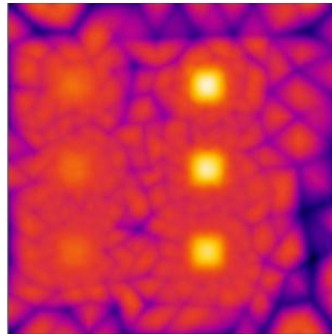
Thickness of defect	2 mm	5 mm	10 mm
Left	0.268	0.267	0.264
Centre	0.269	0.267	0.265

Right	0.272	0.27	0.269
Average	0.270	0.268	0.266
Actual depth	0.27	0.27	0.27
Error %	0.12	0.74	1.48

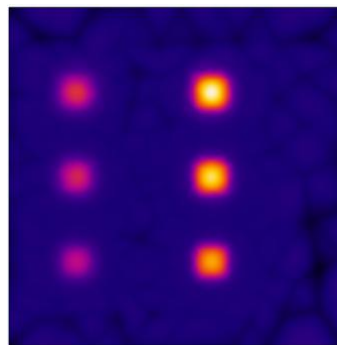
The results shown below are for slab subjected to thermal excitation in form of sinusoidal wave having time period 5 minutes and amplitude 1000 W designated as wave type III. The thermograms taken at various times are shown in Figure 37.



(a)



(b)



(c)

Figure 37 Thermograms at a) 7.5 minutes b) 17.5 minutes c) 60 minutes

It is observed from Figure 37 that thermal images of wave type III are similar to those obtained in wave type I and type II. The surface temperature variation is shown in Figure 38.

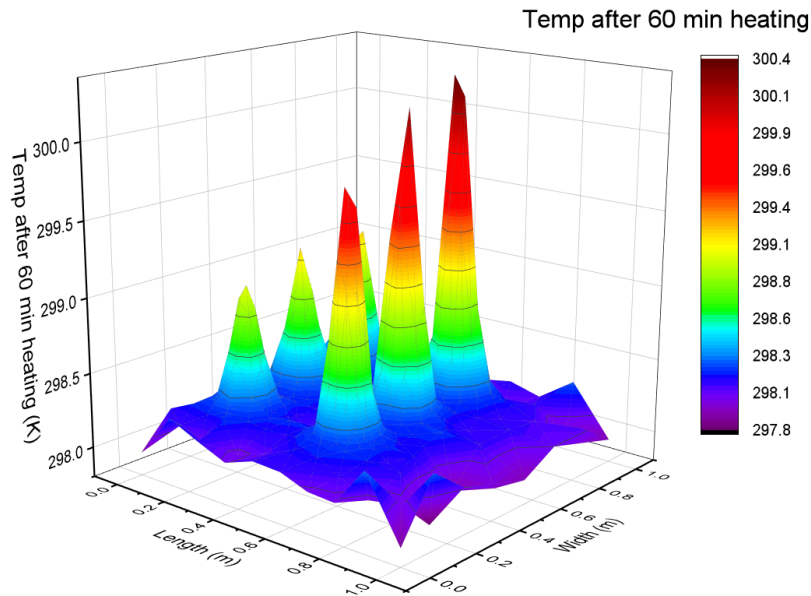


Figure 38 Surface temperature variation after 60 minutes thermal excitation

The depth of defect is measured from temperature contours using indirect method developed in this study. The results are shown in Table 18 and 19.

Table 18 Comparison between actual and measured values of depth for defects located 20 mm from surface of wave type III

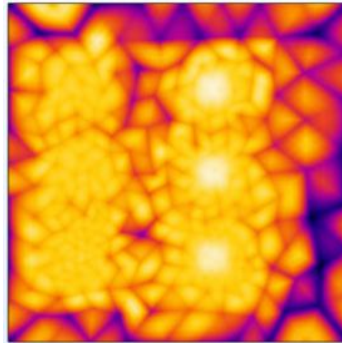
Thickness of defect	2 mm	5 mm	10 mm
Left	0.278	0.276	0.275
Centre	0.279	0.276	0.274
Right	0.276	0.277	0.275
Average	0.278	0.276	0.275
Actual depth	0.28	0.28	0.28
Error %	0.83	1.31	1.90

Table 19 Comparison between actual and measured values of depth for defects located 20 mm from surface of wave type III

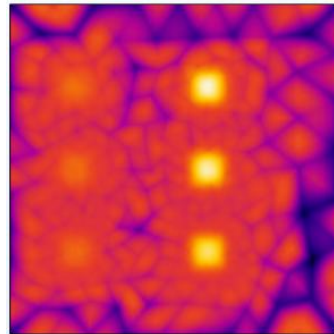
Thickness of defect	2 mm	5 mm	10 mm
Left	0.268	0.266	0.264
Centre	0.27	0.269	0.271

Right	0.264	0.263	0.263
Average	0.267	0.266	0.266
Actual depth	0.27	0.27	0.27
Error %	0.99	1.48	1.48

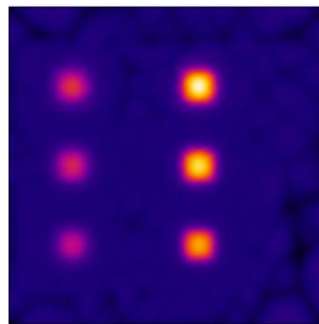
The results shown below are for slab subjected to thermal excitation in form of sinusoidal wave having time period 10 minutes and amplitude 1000 W designated as wave type IV. The thermograms taken at various times are shown in Figure 39.



(a)



(b)



(c)

Figure 39 Thermograms at a) 7.5 minutes b) 17.5 minutes c) 60 minutes

The surface temperature variation is shown in Figure 40. It is observed that surface temperature is lower as compared to wave type I, II and III.

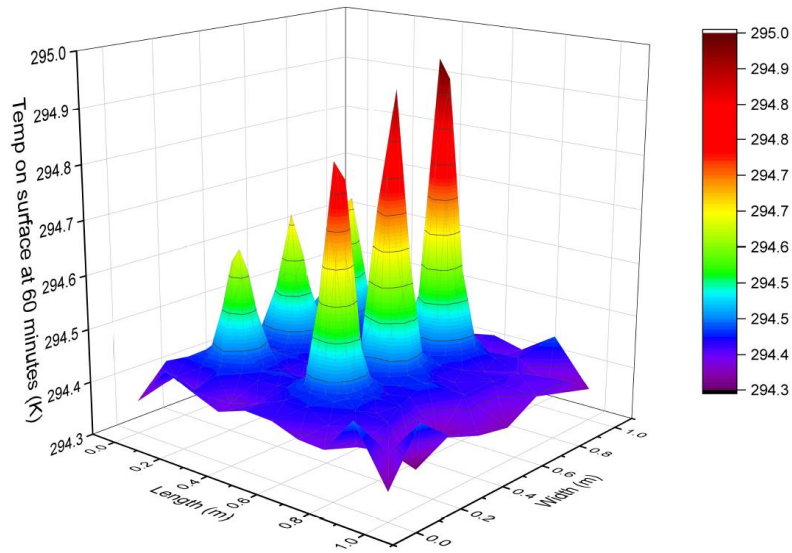


Figure 40 Surface temperature variation after 60 minutes thermal excitation

Same as in the above cases vertical temperature variation is plotted and depth of defect was measured from temperature contours. Results are shown in Table 20 and 21.

Table 20 Comparison between actual and measured values of depth for defects located 20 mm from surface of wave type IV

Thickness of defect	2 mm	5 mm	10 mm
Left	0.278	0.277	0.275
Centre	0.279	0.276	0.273
Right	0.276	0.277	0.275
Average	0.278	0.277	0.274
Actual depth	0.28	0.28	0.28
Error %	0.83	1.19	2.02

Table 21 Comparison between actual and measured values of depth for defects located 30 mm from surface of wave type IV

Thickness of defect	2 mm	5 mm	10 mm
Left	0.268	0.267	0.264
Centre	0.27	0.268	0.268

Right	0.265	0.264	0.264
Average	0.268	0.266	0.265
Actual depth	0.27	0.27	0.27
Error %	0.86	1.36	1.73

The results are obtained for four different thermal excitations considered in this study i.e. 500 W amplitude and 5-minute time period (Wave Type I), 500 W amplitude and 10-minute time period (Wave Type II), 1000 W amplitude and 5-minute time period (Wave Type III) and 1000 W amplitude and 10-minute time period (Wave Type IV). The percentage of error between actual depth of damage and depth extracted from the temperature contour map is calculated and tabulated in Tables 14 to 21. It is observed that by utilizing this method for defect depth detection, the maximum error percentage is 2.22%. The variation of percentage error in depth detection for different defect thicknesses and wave types is plotted as shown in Figure 41.

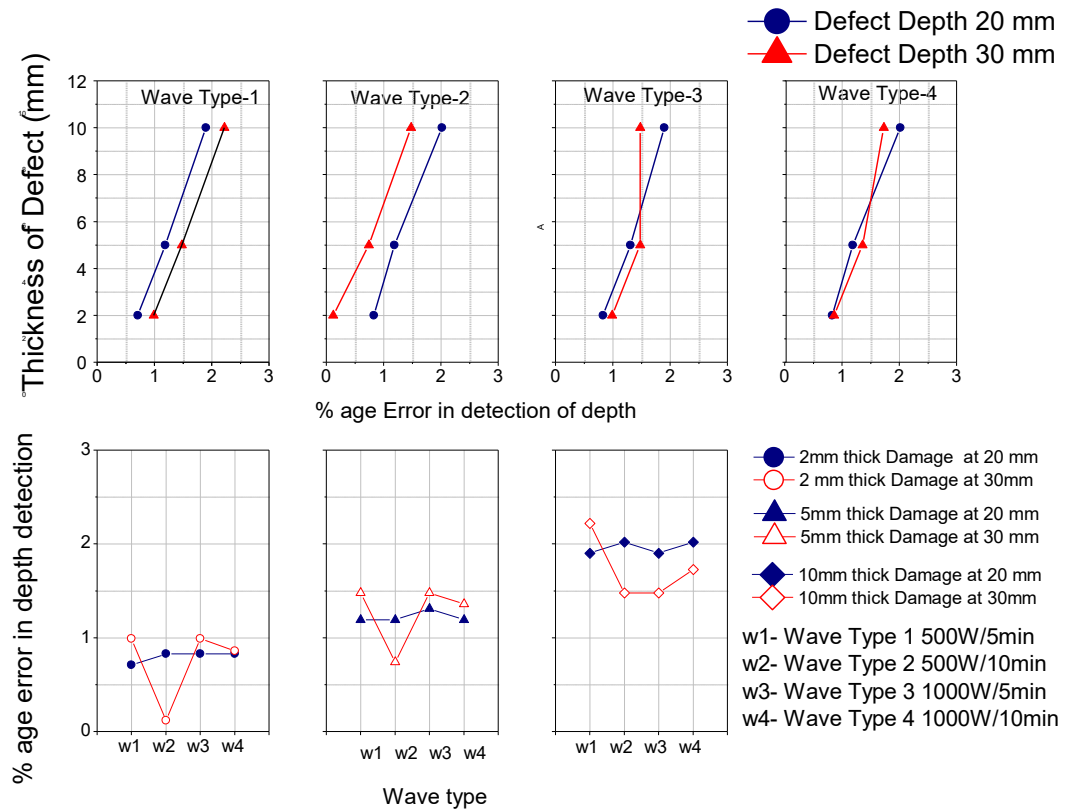


Figure 41 Percentage error between actual depth of defect and depth obtained from simulation

4.5 Observations

It is observed from Figure 41 that type of wave does not have effect on defect depth detection. The percentage error between actual depth of defect and depth obtained from temperature contour is about 2% which is fairly accurate. It is also observed that as thickness of defect increases the error between actual depth and depth obtained from temperature contour increases. The method uses contour plot of thermal image of slab cross section obtained using FEA simulation, hence it is called indirect method. It is demonstrated that the method of finding defect depth by plotting contours on vertical sections is effective in accurately estimating defect depth. In actual practice method developed in this study can be applied on validated FEA simulation. As per my findings, the method developed in this study can be adopted in the field within range of 2% error as observed in Figure 41. The error between the experiment and FEA simulation results can be due to factors like variation in ambient temperature, convection currents, reflection from other objects, non-uniform thermal excitation, variation in emissivity, etc. The Table 10 highlights the errors in results obtained from FEA simulation and experiments. This method aims to enhance accuracy by combining the strengths of FEA and thermographic data. The method follows the approach adopted by many researchers like *Hiasa et al., (2018)* & *Cannas et al., (2012)*. The findings presented in this chapter have been documented in the publications of *Naik et al., (2022)*.

Chapter 5

Direct method to calculate defect depth based on thermal contrast

5.1 Outline of study

The Figure 42 depicts the methodology followed to develop direct method to calculate defect depth based on the thermal contrast method.

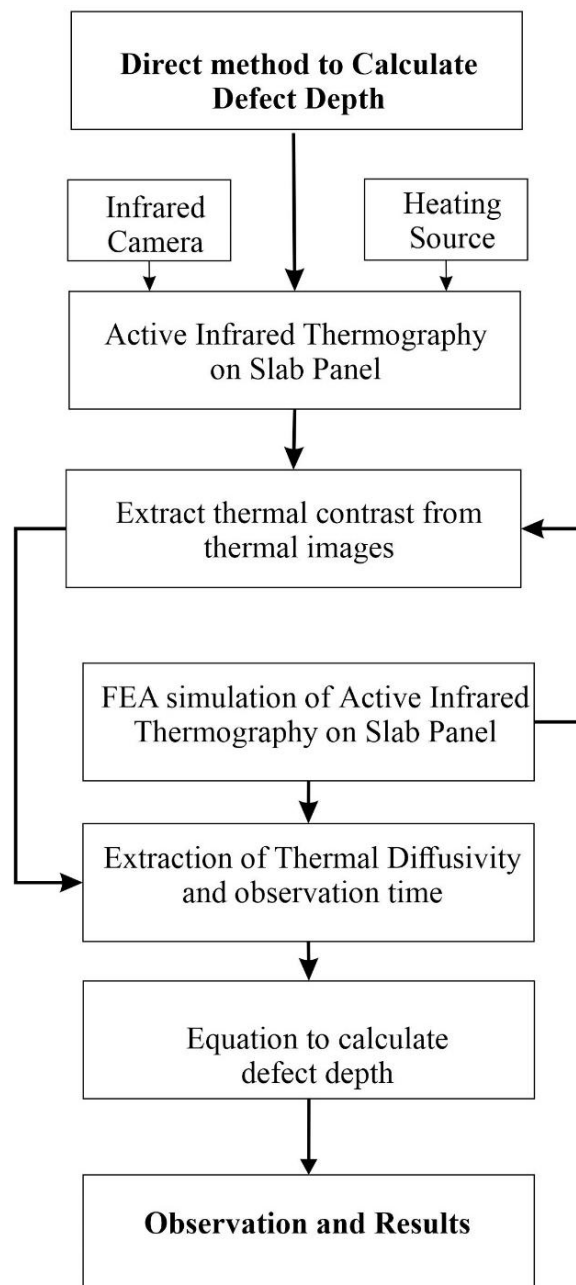


Figure 42 Flowchart of methodology to develop direct method to obtain defect depth

5.2 Objectives and scope

The chapter 4 explained indirect method to calculate depth of defects using validated FEA simulation. The method involves the application of Lock in thermography and plotting of temperature data extracted from vertical sections in form of contour. However, this method can be applied only to validated FEA simulations. Also, it is difficult to get temperature data by taking vertical sections on an actual slab. The current chapter introduces a technique taking into account practical difficulties experienced while implementing infrared thermography in the field. The method utilizes the concept of absolute thermal contrast to predict the depth of subsurface defects. The aim is to develop a technique to identify the depth of subsurface defects in reinforced cement concrete (RCC) structures. The objective is to formulate improvements on a technique developed by *Huh et al., (2018)* to identify the depth of subsurface defects in reinforced cement concrete (RCC) structures. This study was conducted to modify infrared thermography as a suitable non-destructive testing method in construction field which can identify defect depth accurately.

Infrared thermal images are 2D images which show only location of defect. The data from images needs to be extracted and processed so that meaningful information like depth and area of defect is obtained. To conduct study outlined in this chapter, an RCC slab with subsurface defects at various depths is cast. The main focus is to conduct pulsed thermography experiments with different heating regimes on the laboratory cast RCC slab. An infrared camera is used to record several sequences of surface thermal images of the RCC slab embedded with defects. The data from recorded thermal images is processed to estimate the absolute thermal contrast on the image where defect hotspots are visible. A correlation is observed between defect depth, observation time, absolute thermal contrast between the damage zone and the sound or undamaged area and the thermal properties of the concrete. The recorded thermogram will be used to produce a generalized equation that can help predict depth of damage in concrete structures. The equation will be compared to depth equation developed by *Huh et al., (2018)* for efficiency. The main focus is to conduct pulsed thermography experiments with different numbers of heating regimes on an RCC slab embedded with defects. An equation for predicting the defect depth from the surface of a slab is obtained by plotting the depth of the defect against the delay time or observation time. This chapter introduces an improved technique to predict the depth of subsurface defects using the absolute thermal contrast method.

5.3 Experimental study

5.3.1 Casting of concrete Slab

An experiment is designed to develop direct method to calculate defect depth. For the experiment an RCC slab of grade M30 having size 50 cm x 50 cm x 12 cm is cast. A design mix is prepared to calculate quantity of materials required to cast the RCC slab as shown in Table 22. The w/c ratio adopted for the concrete mix is 0.4 and quantity of super plasticizer is 0.8% by weight of cementitious material.

Table 22 Quantity of materials used for casting the slab

Cement	Water	Coarse Aggregate (20 mm)	Coarse Aggregate (10 mm)	Fine Aggregates
13.03 kg	5.21 L	20.41 kg	20.41 kg	23.83 kg

A wooden mould 50 cm x 50 cm x 12 cm in size is fabricated and used for casting of the concrete slab. The reinforcement is placed in the form of a square mesh consisting of 4 bars of 8 mm diameter at 130 mm c/c equal spacing in both the directions. The artificial damages in the slab are created using thermocol pieces placed at the time of concreting as shown in Figure 43.

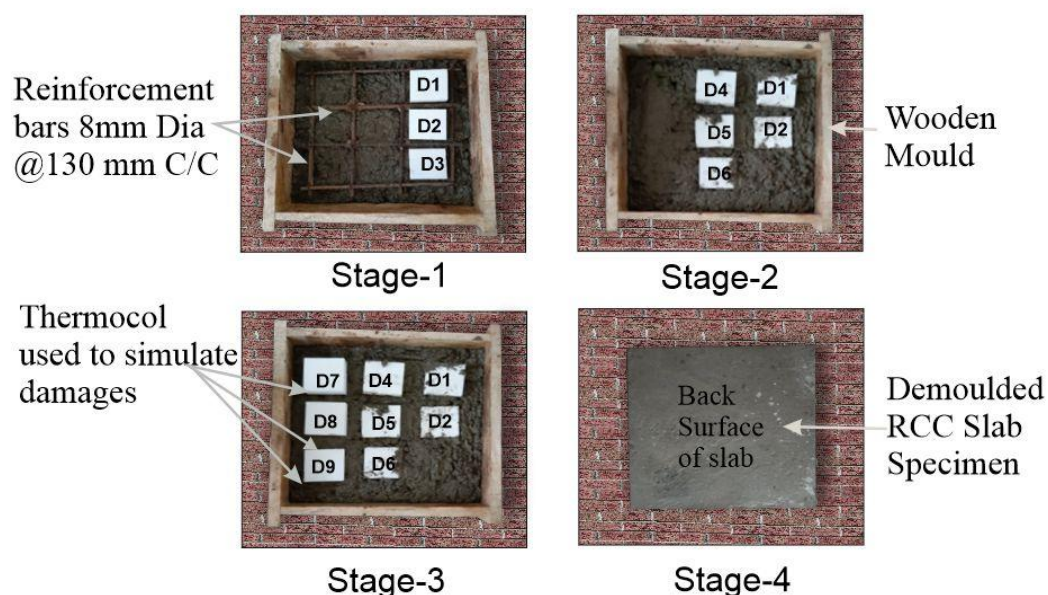


Figure 43. Casting of the concrete slab

The Figure 43 shows the various stages of slab concreting and subsurface defect placement used for this study. The concrete is filled to a depth of 2 cm, after which the reinforcement

bars are placed along with defects D1, D2 and D3. This is as shown in stage-1. The stage-2 is the phase where concrete is filled to a depth of 3 cm, and defects D4, D5 and D6 are placed. In stage-3 concrete is filled to a depth of 5 cm, and defects D7, D8 and D9 are placed. The stage 4 shows the back surface of the finished RCC slab. The slab is demoulded after 48 hours and subsequently cured as per Indian Standards (IS) code.

The dimensions of the thermocol (Polystyrene) pieces D1-D9 adopted as defects inside the RCC slab are as shown in Table 23 along with location and depth of defects.

Table 23 Sizes of defects embedded in the slab

Label	Length (mm)	Width (mm)	Thickness of defect (mm)	Depth from top surface (mm)	Width to Depth Ratio (WTDR)
D1	100	100	50	20	5
D2	100	100	30	20	5
D3	100	100	10	20	5
D4	100	100	50	30	3.33
D5	100	100	30	30	3.33
D6	100	100	10	30	3.33
D7	100	100	50	50	2
D8	100	100	30	50	2
D9	100	100	10	50	2

The Figure 44 shows artificial damage i.e., thermocol pieces D1 to D9, placed at different depths in the slab. The thermocol pieces D1, D2 and D3 are located 20 mm from the front surface of the slab; D4, D5 and D6 are located 30 mm from the front surface of the slab; and D7, D8, and D9 are located 50 mm from the front surface of the slab. The size and layout of the different thermocol pieces used to create damage in the slab is shown. The pulsed thermography is conducted on the front surface of the slab. Sections AA, BB, CC and DD show the depths of damage D1 to D9 from the front surface of the slab.

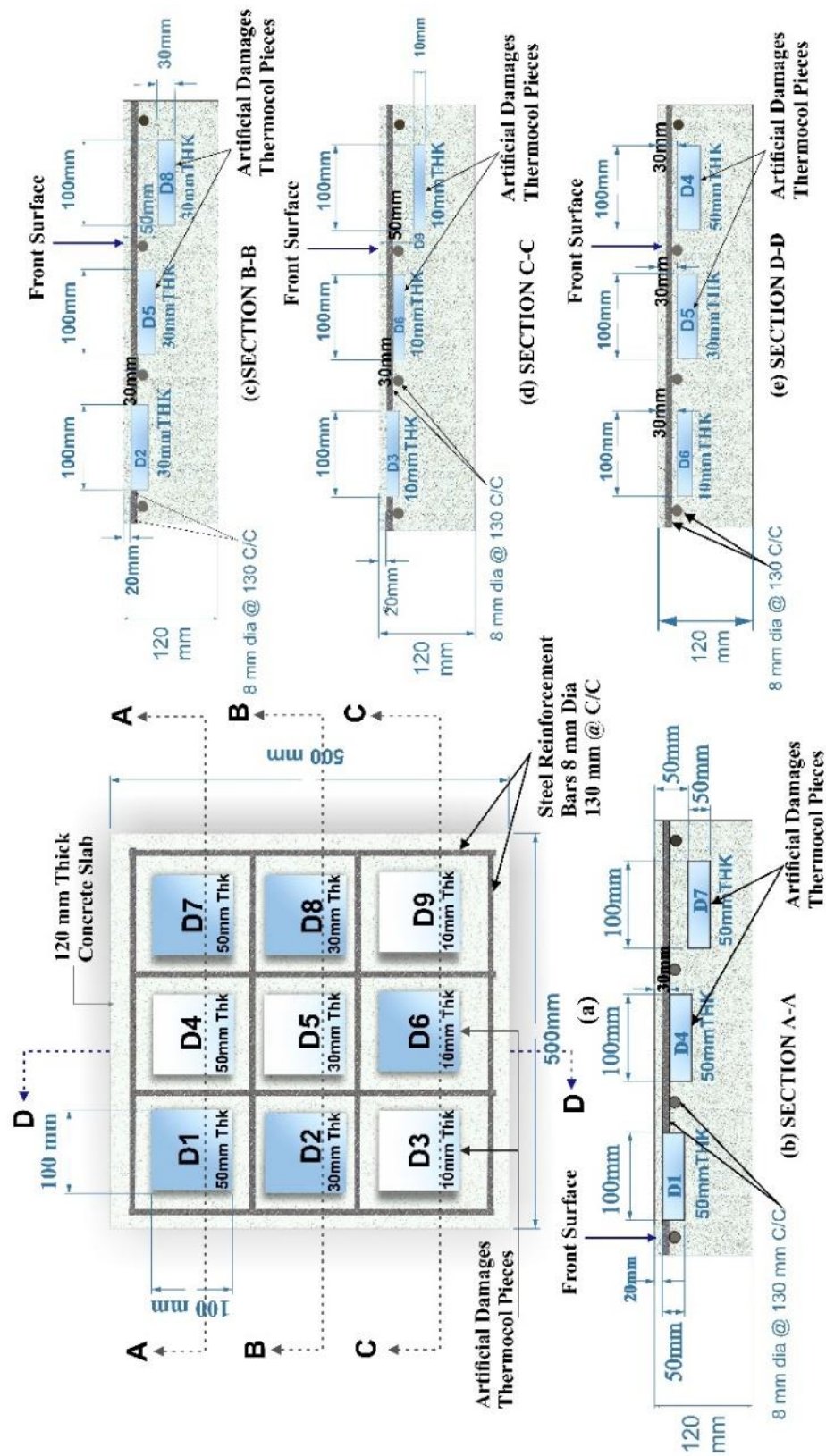


Figure 44 a) Front surface of the slab showing the layout of the planned subsurface defects in the concrete slab

(b) Section AA (c) Section BB (d) Section CC (e) Section DD

5.3.2 Experimental setup

The pulsed thermography is a type of active infrared thermography in which the surface of concrete structure is subjected to a pulse having a duration varying between few microseconds to few minutes. To conduct pulse thermography, four halogen lamps out of which two are of 1000 W and other two of 500 W wattage are used. The lamps are used as heating sources. They were mounted on a frame that is specially fabricated for the experiment as shown in Figure 45. An autotransformer is used to control the power output of halogen lamps. The frame with halogen lamps mounted on it was located at 1 m from the front surface of the slab. An infrared camera (FLIR A325) was placed 2 m from the front surface of the slab in order to obtain a full image of the slab surface. FLIR A325 is an uncooled recording type infrared camera with a resolution of 320 x 240 and a maximum frame rate of 60 Hz. The FLIR Research IR software installed on a laptop, as shown in Figure 45 below is used to control the input parameters and recording time of the infrared camera.

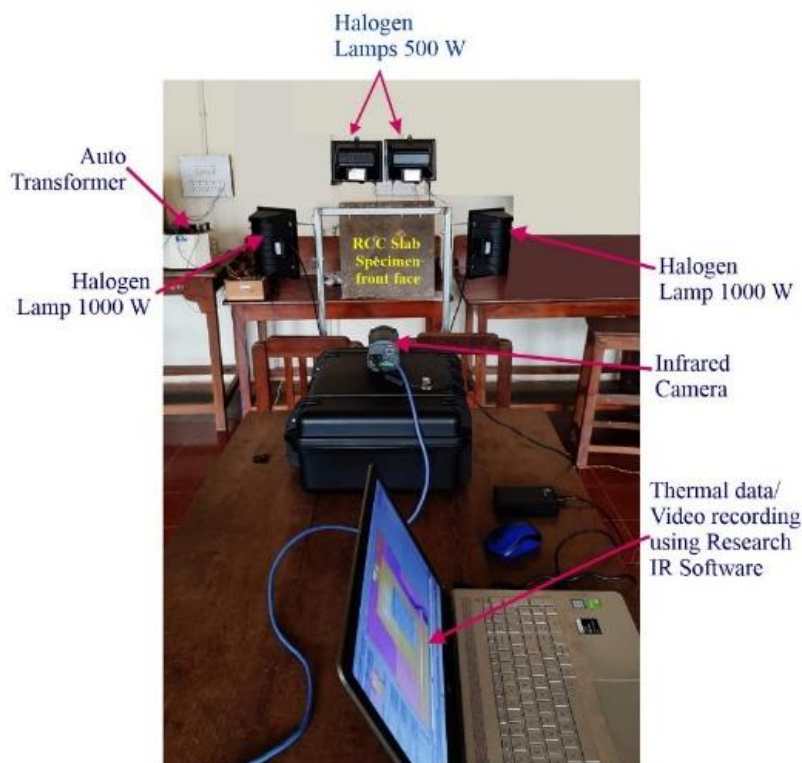


Figure 45 Experimental setup with a recording type infrared camera

FLIR A325 infrared camera captures several sequences of surface thermal images of the of the RCC slab at an optimal frame rate of 15 Hz. Technical specifications of the camera are shown in Table 24.

Table 24 Technical specifications of the FLIR A325 infrared camera

Items	Parameters
Temperature measurement range	-20 ⁰ C to +120 ⁰ C (-4 ⁰ F to 248 ⁰ F) 0 C to +250 C (32 F to 662 F)
Thermal sensitivity (NETD)	<50 mK
Time constant	<12 ms
Maximum frame rate	60 Hz
Detector type	320 x 240
Infrared spectral band	7.5 μ m to 13 μ m
Temperature measurement accuracy	$\pm 2^0$ C or $\pm 2\%$ of reading.

5.4 Pulsed thermography experiment

Raja et al., (2019) carried out a series of experimental and numerical studies to study the effect of wind velocity and rate of heat flux on thermal contrast. It is found that thermal contrast is reduced due to increased wind velocity and the impact of wind is more pronounced for deeper defects. The thermal contrast is dependent on total heat absorbed rather than duration and intensity. In the current study, an FEA model validated with experimental results found that only 6.45% of heat output of halogen lamps is absorbed by the concrete surface. A minimum value of 1°C is suggested as a safe value for thermal contrast. In the current study applied heat flux is enough to generate the required thermal contrast for defects to be visible. Huh et al., (2018) cast concrete slabs with embedded defects of same size at varying depths. The authors used absolute thermal contrast method to determine observation time and proposed non dimensional factor k. This factor k is used to develop linear equation to predict defect depth. The study presented in this chapter proposed to introduce a non-linear equation to predict defect depth by relating it with thermal length. The thermal length is defined as square root of product of thermal diffusivity and observation time. It is found that thermal contrast varies non-linearly with time. The equation introduced in the paper presents more accurate value of

depth. Pozzer et al., (2024) explored passive IRT capabilities on reinforced concrete slab, unreinforced concrete slab and reinforced concrete column. The authors used the thermal contrast method and principle component thermography for post processing of raw thermal images. They found that defects with size to depth ratio of more than or equal to 2 were detectable by the thermal contrast method. The passive thermography technique requires continuous collection of data over various seasons and the formation of maximum thermal contrast is dependent on various ambient environmental conditions. The studies conducted by several authors referenced above have been instrumental in demonstrating the efficiency of thermal contrast method in predicting defect depth. Many studies have established direct relations between depth of defect and thermal contrast for concrete slabs taking into account their material properties. These researches not only support the theoretical framework of our study but also contribute to optimizing the application of this method in real-world scenarios. By comparing the methodologies and results of these studies, we reinforce the reliability of our proposed approach.

In this study, the laboratory casted RCC slab was heated under two different heating regimes of 10 minutes and 20 minutes. The above two heating times were chosen considering practical applications. If the heating time is greater than 20 minutes, then the temperature of the defect and sound region becomes almost same. This results in negligible thermal contrast. In such a situation, defects are not visible. Hence the duration of thermal excitation is fixed taking into consideration thermal contrast development and field conditions. This is verified from experimental results. Two sets of experiments were conducted for each heating regime to average out the error due to any experimental slip-up. The heating regime indicates the total time the slab is heated, after which the heat source is turned off. However thermal data recording by an infrared camera continues during the cooling phase. The cooling phase was included as per the findings by Adeli et al., (2018) that defects are visible more clearly when structure is cooling after direct sunlight or early morning when structure is heating after cooling overnight. The total thermal data recorded by the infrared camera for each heating regime is 43 minutes, which included heating and cooling phases. The thermal data recorded by an infrared camera were set at an optimal frame rate of 15 Hz.

The absolute thermal contrast method adopted by Hiasa et al., (2017), Cotic et al., (2015), Hiasa et al., (2018) & Pozzer et al., (2024) is used in this study to analyse the sequence of thermal images captured by the infrared camera. Many researchers adopt this technique and they conclude that there exists a relationship between defect depth and thermal contrast. The FLIR Research IR software is utilized to extract thermal data of slab surface at every one

minute interval. By utilizing this software, a region of interest is selected on the defect area and sound area, as shown in Figure 46(c). The defect area was selected based on the color contrast visible in the thermal images, as shown in Figure 46(c). The numbers of pixels in the thermal image of the slab were calibrated with the actual dimensions of the slab to determine how to convert the number of pixels to the distance in centimetres. The image obtained by the IR camera is shown in Figure 46 (c), where the region of interest (ROI) is marked. The image in Figure, which shows the difference in color contrast over D1, is used to explain the procedure for obtaining the absolute thermal contrast. An enlarged view of the thermogram over defect D1 is shown in Figure 46 (a). The defect created at location D1 is 20 mm from the front surface of the slab and clearly shows color contrast.

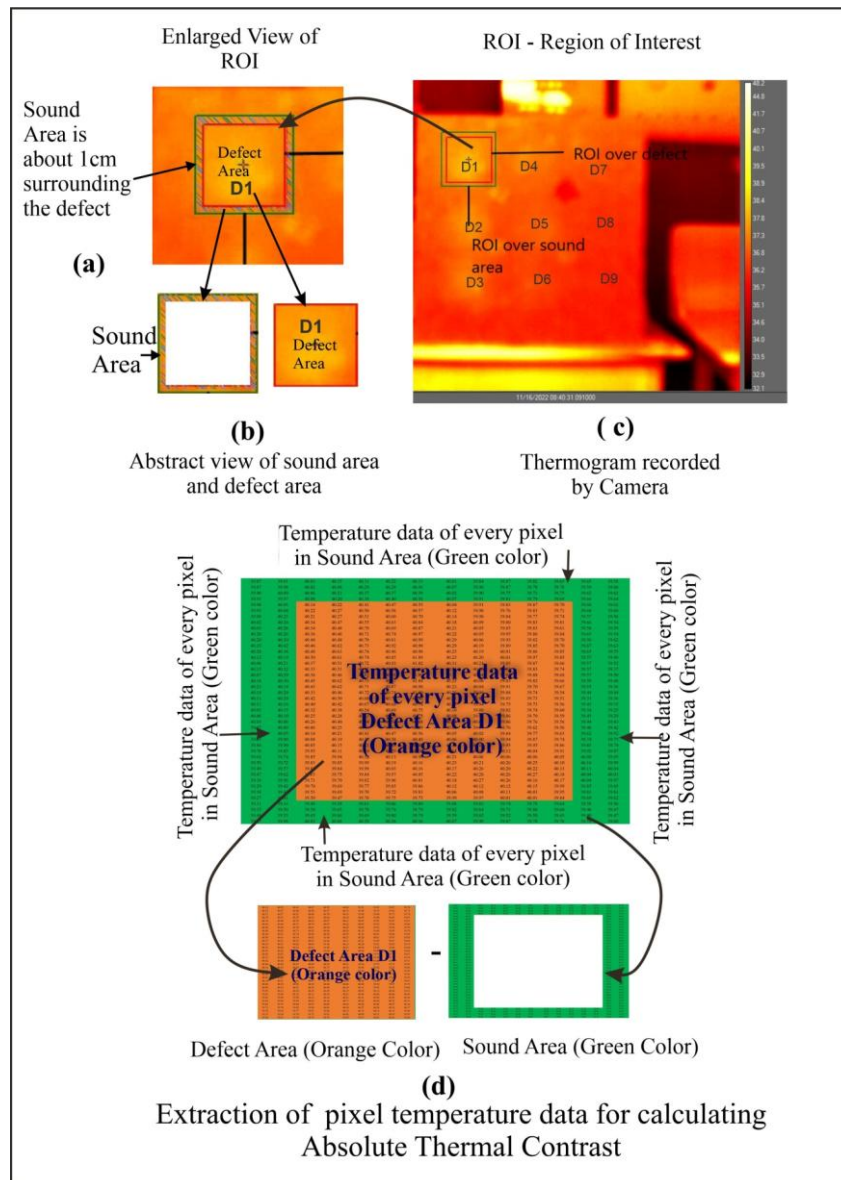


Figure 46 Selection of regions of interest (ROIs) across and sound areas

The sound area is selected 1 cm from the boundaries of the defect where the temperature is approximately 1-2°C lower than the temperature above the defect area. The temperature data

from the defect and sound areas is extracted using Research IR software at interval of one minute over entire duration of the thermal recording, as illustrated in Figure 46(d). The maximum temperature over the entire set of temperature data is recorded for every one minute interval. The same procedure is repeated for sound area. The difference in the maximum temperature across the defect area and the sound area is then calculated for every minute from the moment the thermal excitation source is switched on till the end of the recording time. The absolute thermal contrast is calculated as per Equation 8 below

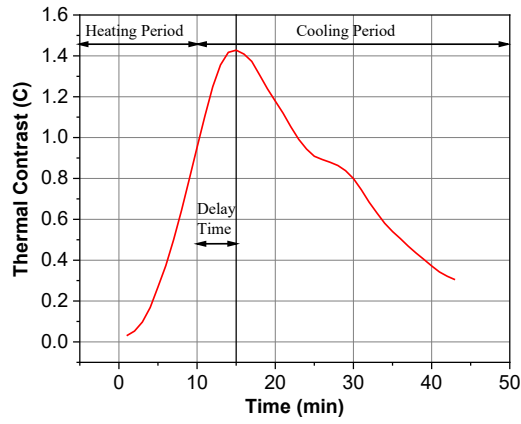
$$\text{Absolute Thermal Contrast} = \text{Max Temp}(\text{Defect Area} - \text{Sound Area}) \quad (8)$$

The absolute thermal contrast is plotted versus time, from which the observation time or delay time was obtained. The observation time or delay time is defined as the gap between the time at which the peak thermal contrast is obtained to the time at which the heat source is switched off. The observation time or delay time ($T_{\max}$) is obtained from the thermal contrast variation plot as seen in Figure 47, Figure 48, Figure 50 and Figure 51. An empirical equation is developed to predict the depth of defects. The equation is compared with similar equation developed by *Huh et al., (2018)*.

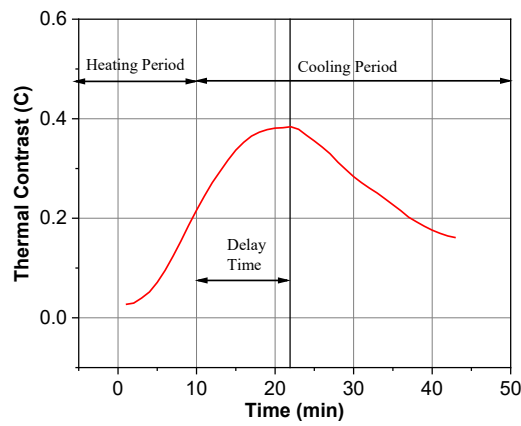
5.5 Results and Discussions

5.5.1 Ten-minute heating regime

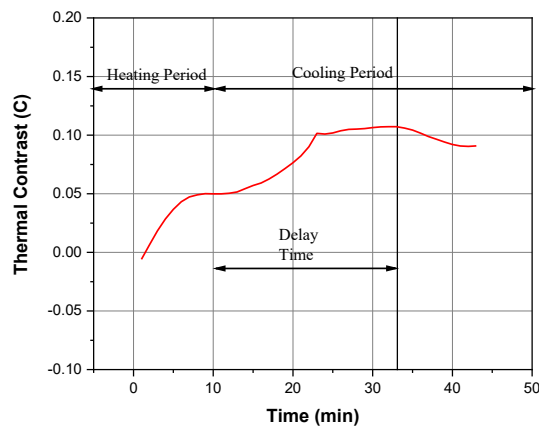
In this section, the thermal contrast, and delay time obtained for slabs subjected to a ten-minute heating regime are presented. Two sets of experiments were conducted for this heating regime. The surface of the slab is heated with halogen lamps, as shown in Figure 45, for ten minutes after which the lamps are turned off. However the thermal data is recorded during the cooling phase for a total of 43 minutes. The obtained thermal image sequences are subsequently processed to obtain the absolute thermal contrast, which is subsequently plotted versus time as explained in an earlier section. Figure 47 a shows the variation in the absolute thermal contrast with time for a defect located 2 cm from the front surface of the slab. Similar plots were made for defects located at depths of 3 cm and 5 cm as shown in Fig 47 b and c.



(a) Defect depth 2 cm - 10 min heating regime



(b) Defect depth 3 cm - 10 min heating regime

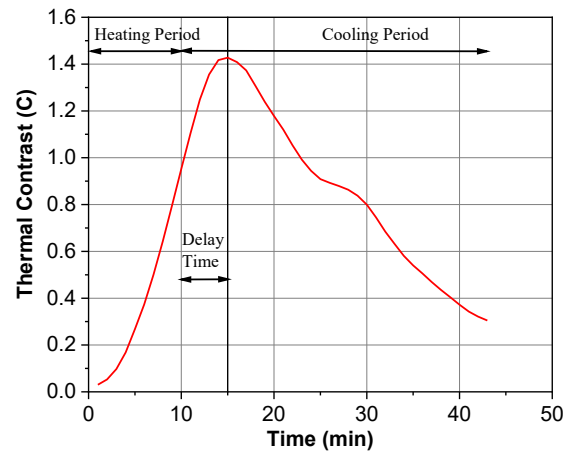


(c) Defect depth 5 cm - 10 min heating regime

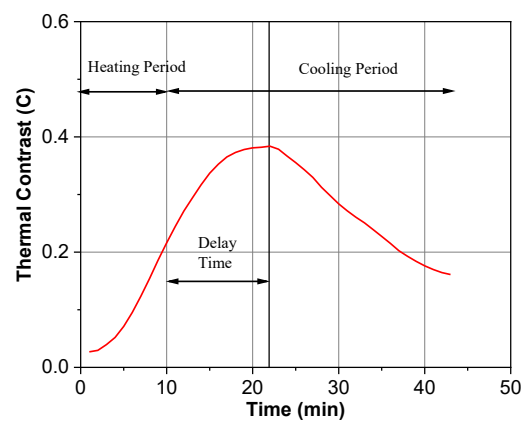
Figure 47 Absolute Thermal Contrast variation - 10 min heating regime

Figure 47 shows that the absolute thermal contrast reaches a peak a few minutes after the heat source is turned off. Figure 47 also shows that the absolute thermal contrast varies like a polynomial function, which is obtained by extrapolation after smoothing the data. The Figures

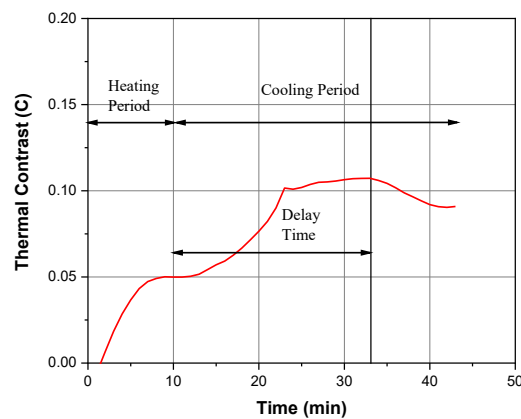
47 and 48 shows that delay time or observation time increase with defect depth. A second set of experiments is conducted to verify the above results. The delay time or observation time recorded from both sets of experiments are subsequently plotted versus the depth of the defect. A nonlinear function was fit between the obtained data points, with $R^2=0.99$.



(a) Defect depth 2 cm



(b) Defect depth 3 cm



(c) Defect depth 5 cm

Figure 48 Absolute Thermal Contrast variation - 10 min heating regime (Second set of experiments)

The observation times for all defect depths are obtained and plotted vs depth of defect as shown in Figure 49. A nonlinear curve was fitted over the obtained data sets with $R^2 = 0.99$. Results of both experimental sets are plotted as seen in Figure 49.

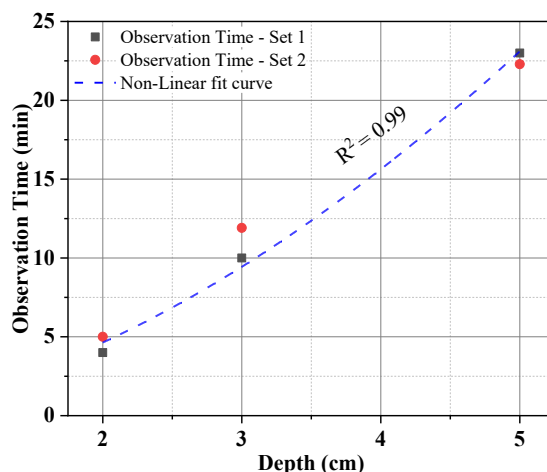
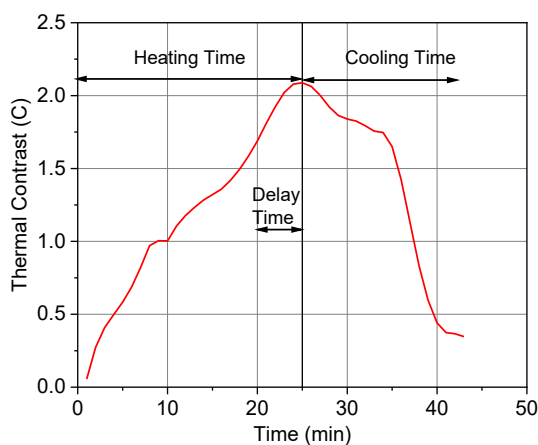


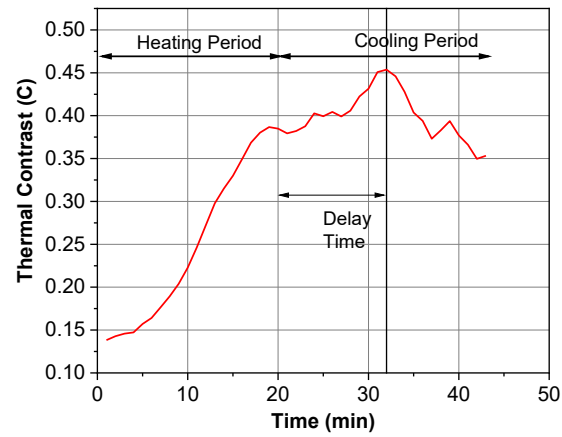
Figure 49 Variation of observation time with depth in the 10 minute heating regime

5.5.2 Twenty-minute heating regime

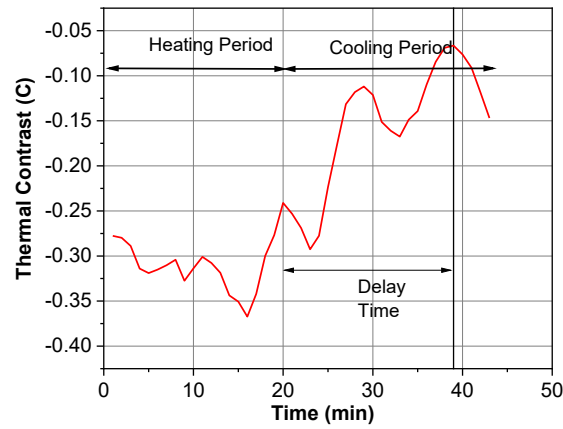
Two sets of experiments are conducted for the twenty-minute heating regime. The surface of the slab is heated with halogen lamps for twenty minutes, after which the lamps were turned off. The temperature variation on the slab surface is recorded for an entire duration of 43 minutes, which included heating and cooling phases. Figure 50 shows the variation in thermal contrast with time for all defect depths.



(a) Defect depth 2 cm



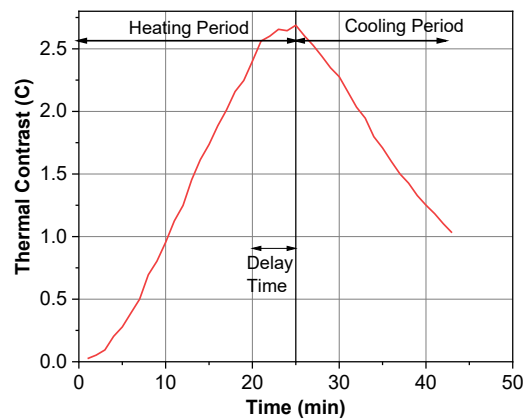
(b) Defect depth 3 cm



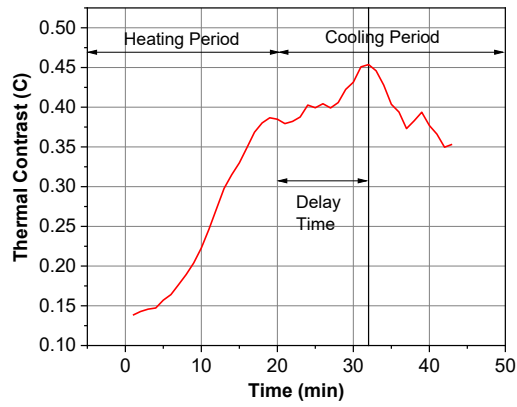
(c) Defect depth 5 cm

Figure 50 Absolute Thermal Contrast variation – 20 minute heating regime

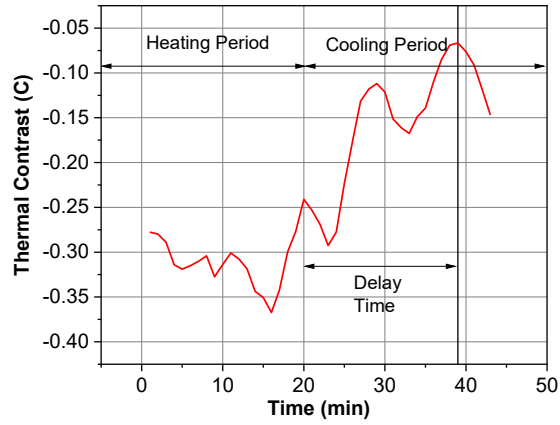
The results of the second set of experiment performed for the same heating regime are shown in Figure 51. The observation times from both the experimental sets were plotted versus defect depth as shown in Figure 52.



(a) Defect depth 2 cm - 20 min heating regime



(b) Defect depth 3 cm - 20 min heating regime



(c) Defect depth 5 cm - 20 min heating regime

Figure 51 Absolute Thermal Contrast variation - 20 min heating regime (Second set of experiments)

The Figure 52 shows that delay time or observation time for 20-minute heating regime is almost the same as that for the 10-minute heating regime. The Figure 52 also shows the variations in delay time and observation time with respect to the depth of the defect when the slab is subjected to 20-minute heating regime. A nonlinear function is fit between the obtained data points, with $R^2=0.908$.

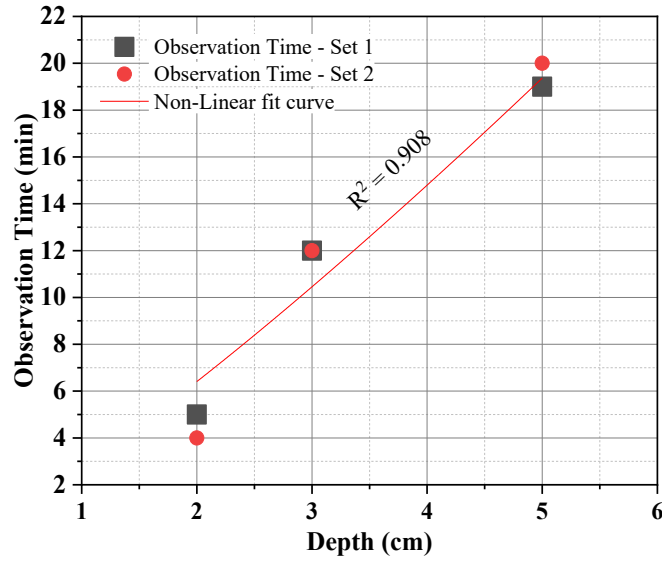
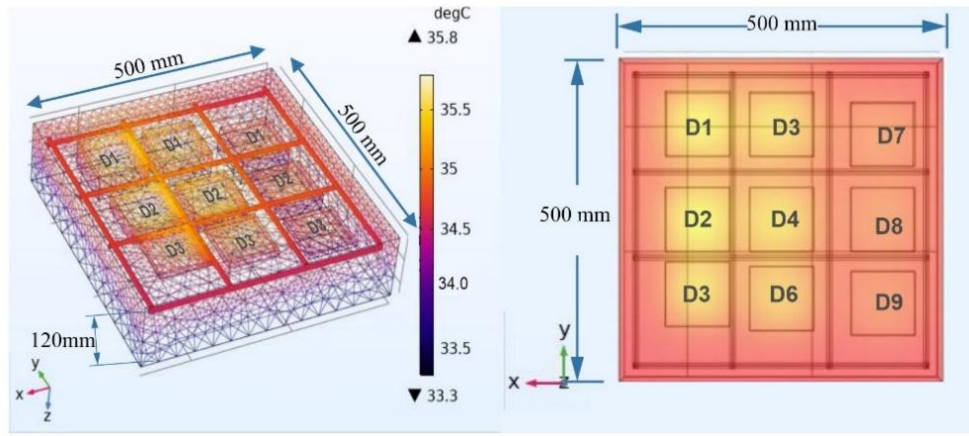


Figure 52 Variation in observation time with respect to the depth of 20-minute heating regime

Figure 49 and Figure 52 clearly indicate that the observation time varies nonlinearly with the defect depth. The nonlinear variation in observation time is utilized in developing a numerical equation to predict the depth of defects. The observation time is dependent on the thermal properties of the concrete and is quantified using thermal diffusivity. To determine the thermal diffusivity of the RCC slab, a validated FEA simulation is utilized. The slab is modelled in FEA software exactly as per the experimental slab cast in the laboratory. A pulsed thermography experiment performed on the RCC slab is simulated with FEA software. The maximum temperature above the defect from the experiment and FEA simulation is matched. The detailed procedure for obtaining the thermal diffusivity is explained in the section 5.5.3.

5.5.3 FEA simulation to obtain thermal diffusivity

A 50 cm x 50 cm x 12 cm slab with subsurface defects, as shown in Figure 44, is modelled via FEA software. A model of the prepared slab is shown in Figure 53 (a) and 53 (b).



(a)

(b)

Figure 53 a) 3D Meshed FEA model b) Plan view showing defects

The material properties utilized in the FEA simulation are shown in Table 25.

Table 25 Material properties used in the FEA model

Properties	Concrete	Reinforcement
Thermal conductivity k [W/m-K]	1.9	44.5
Heat Capacity C_p [J/kg-K]	900	475
Density ρ [kg/m ³]	2500	7850

The ambient temperature, $T = 33^\circ\text{C}$ recorded during the experiment is applied to the FEA model. To simulate the thermal excitation of the slab, a forced heat flux is directed on front surface of the slab as defined in Equation 9a,

$$-n \cdot q = q_0 \quad (9a)$$

Where q is the heat flux intensity and q_0 represents the applied heat flux intensity as shown in Equation 9b.

$$q_0 = \frac{P_0}{A} \quad (9b)$$

A is the surface area of the specimen, and P_0 is the applied heat power. The external natural convective heat flux is applied to the front surface of the slab model in FEA software to

simulate the effect of wind on the surface temperature. This boundary condition is applied as per Equation 10.

$$q_0 = h \times (T_{\text{ext}} - T) \quad (10)$$

where h is the convection coefficient, and T_{ext} represents the atmospheric temperature. The surface-to-ambient radiation boundary condition is applied as per Equation 11.

$$-n \cdot q = \varepsilon \sigma (T_{\text{amb}}^4 - T^4) \quad (11)$$

where T_{amb} represents the ambient temperature, T represents the temperature of the slab, ε represents the surface emissivity of the concrete slab, σ represents the Stefan-Boltzmann constant and q is the heat flux intensity. The maximum temperature above the defect in FEA simulation closely matched the maximum temperature recorded during the laboratory experiment when power in FEA simulation (P_0) is 160 W. Multiple trials of pulsed thermography simulations were carried out with varying heat flux values to match the maximum temperature above the defect, as obtained in the laboratory experiment.

The Figure 53 shows the variation in the maximum temperature over defect D4 located at a depth of 3 cm. The graph compares maximum temperature of FEA simulation and experiment. The maximum thermal contrast occurs during the cooling period, as shown in Figures 47 & 48 as well as 50 & 51. This shows that the FEA model is capable of clearly representing the experimental observations. Hence, the FEA simulation is validated with experimental data. The thermal properties utilized in the validated FEA simulation are used to calculate the thermal diffusivity as per Equation 12.

$$\alpha = \frac{k}{\rho \times c} \quad (12)$$

where k is the thermal conductivity, ρ is the density and c is the specific heat capacity. The thermal diffusivity is related to the depth of the defect.

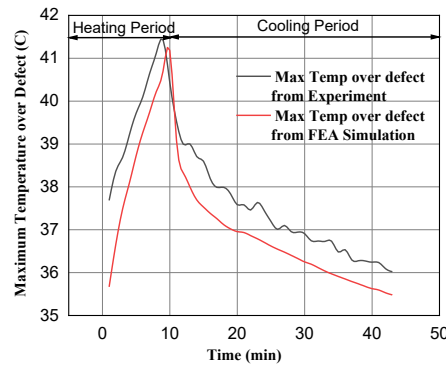


Figure 54 Comparison of maximum temperatures obtained for defect D4

The Figure 55 shows the maximum temperature in both the experimental and FEA simulations obtained during the recording period. The thermal images (thermograms) obtained from the experiment and FEA simulation after a heating period of 10 minutes are shown in Figure 55. From both thermograms, it is observed that defects D1-D6 are visible, while defects D7-D9 are not. The thermogram obtained from the FEA simulation closely matches the thermogram from the laboratory experiment. This proves that the FEA model is validated and represents a similar output from the experiment.

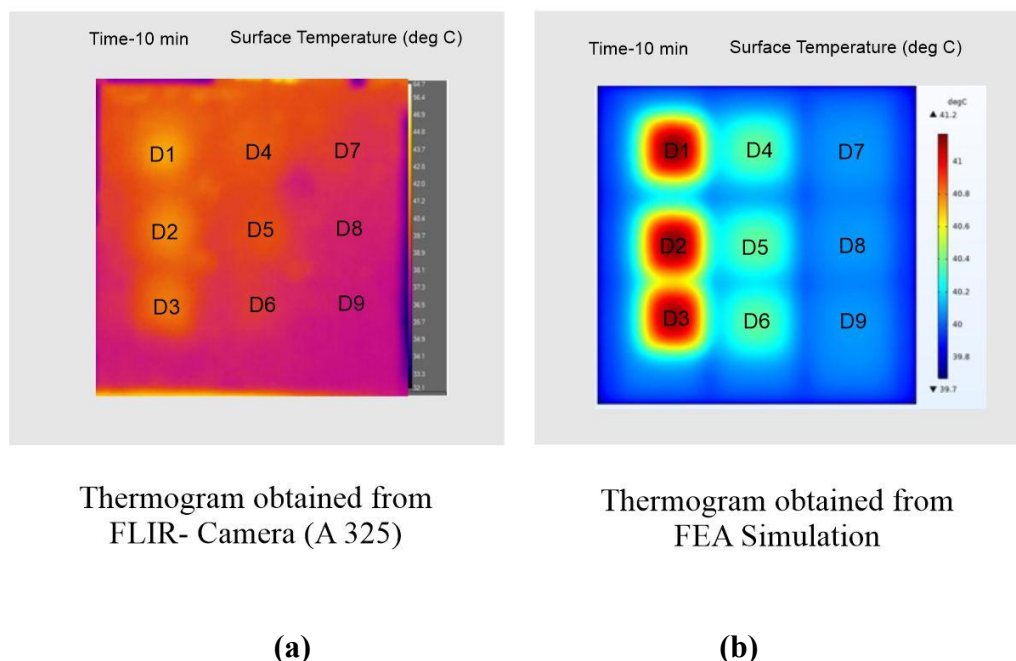


Figure 55 a) Thermogram from an infrared camera b) Thermogram from an FEA simulation with 10 min of heating

5.5.4 Equation to predict depth

When the concrete slab is heated, heat is transferred from the hot to the cold side of the slab. The rate of heat transfer from the hot to cold side of the specimen is obtained by the thermal diffusivity (α). From the experiment, it is observed that there exists a clear relation between the depth of the defect, and the rate of heat transfer inside the RCC slab. The thermal diffusivity multiplied by the observation time (T_{max}) gives the rate of heat travel over the area. The square root of (αT_{max}) gives the length of heat travel along the depth of the slab. The subsurface defect depth can be identified if the length of heat travel across the defect area is related to the depth of the defect. This relation is plotted in Figure 56. A generalized equation is derived from this graph by fitting a quadratic function consisting of thermal diffusivity and observation time. This function is used to determine the depth of defects using observation time from pulsed thermography experiments on the surface of the slab.

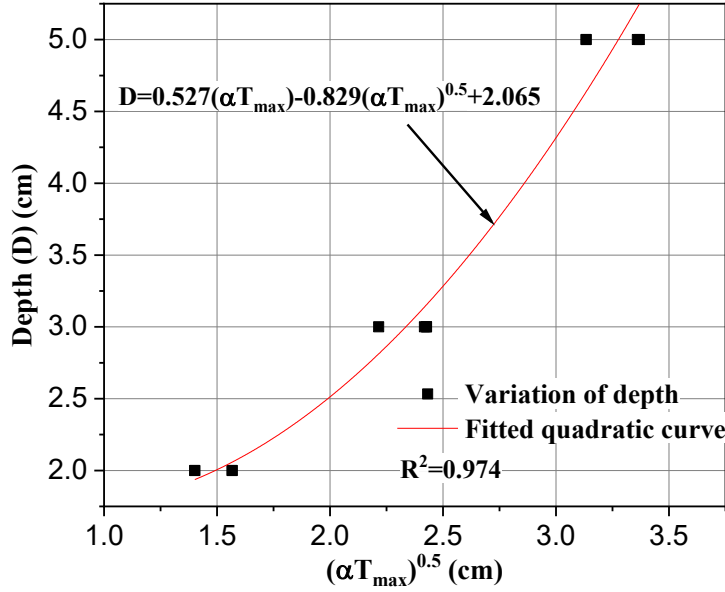


Figure 56 Variation in the depth of the defect (D) with $(\alpha T_{\max})^{0.5}$

In the graph shown in Figure 56, a quadratic function given in equation 13 is fitted on the datasets with $R^2=0.974$.

$$D = 0.527(\alpha T_{\max}) - 0.829\sqrt{\alpha T_{\max}} + 2.065 \quad (13)$$

where $T_{\max}$ is the observation time in minutes, D is the depth of the defect in cm and α is the thermal diffusivity of the concrete. The thermal properties mentioned in Table 24 are used to calculate the thermal diffusivity α of the concrete. *Huh et al., (2018)* developed a relationship for defect depth and $\sqrt{\alpha T_{\max}}$, which is shown in Equation 14:

$$D = k\sqrt{\alpha T_{\max}} - 0.203 \quad (14)$$

where $k=1.395$ is a non-dimensional prefactor.

The Equation 13 is used to calculate the depth of the defect at all locations where damage is identified on the thermogram. The depth of the defect calculated from Equation 14 developed in this study was compared with the equation developed by *Huh et al., (2018)*. The depth of the defect predicted by both equations is shown in Table 26. The table shows that the equation proposed in this study is capable of predicting depth with less error than the equation proposed by *Huh et al., (2018)*.

**Table 26 Comparison between the actual depth and the depth predicted from
Equations 13 and 14**

Actual depth of defect (D) (cm)	Delay Time or Observation Time obtained from experiment (T_{max}) (min)	Square root of Observation time and Thermal diffusivity ($\sqrt{\alpha T_{max}}$) (cm)	Depth predicted using Equation 13 (cm)	Absolute Error %	Depth predicted using Equation 14 (cm)	Absolute Error %
10-minute heating regime						
2	4	1.401	1.94	3.09	1.75	12.40
3	10	2.216	2.82	6.15	2.89	3.73
5	23	3.361	5.23	4.61	4.48	10.30
2	5	1.567	2.06	2.99	1.98	0.86
3	11.91	2.418	3.14	4.74	3.18	5.68
5	22.29	3.369	5.25	5.09	4.50	10.06
20-minute heating regime						
2	5	1.567	2.06	2.99	1.98	0.86
3	12	2.427	3.16	5.26	3.18	6.10
5	19	3.054	4.45	11.01	4.06	18.84
2	4	1.401	1.94	3.09	1.75	12.40
3	12	2.427	3.16	5.26	3.18	6.10
5	20	3.134	4.64	7.15	4.17	16.63

Mean absolute percentage error (MAPE) was utilized to measure error percentage between between the predicted depth and the real depth of defects. The mean absolute percentage error (M.A.P.E.) is defined by the formula given below in Equation 15:

$$\text{M.A.P.E.} = \frac{1}{N} \sum_{i=1}^N \left| \frac{D_{pr} - D_{act}}{D_{act}} \right| \times 100 \quad (15)$$

where D_{pr} represents the predicted depth, D_{act} represents the actual depth and N represents the number of observations. It was found that M.A.P.E. for the depths predicted using equation 13 proposed in this study was 5.12%, whereas the M.A.P.E. for the depths predicted using equation 14 was 8.66%. Hence, the equation developed to predict depth from this study i.e. Equation 13 is able to detect the depth of defects more accurately than what has been reported

in the literature. The depths predicted from both the equations are compared with the actual depth of damage, as shown in Figure 57. In Figure 57, the green bar represents Mean Absolute Error Percentage (M.A.P.E.) of defect depth obtained using Equation 13 developed in this study. The purple bar represents error percentage of defect depth calculated using Equation 14.

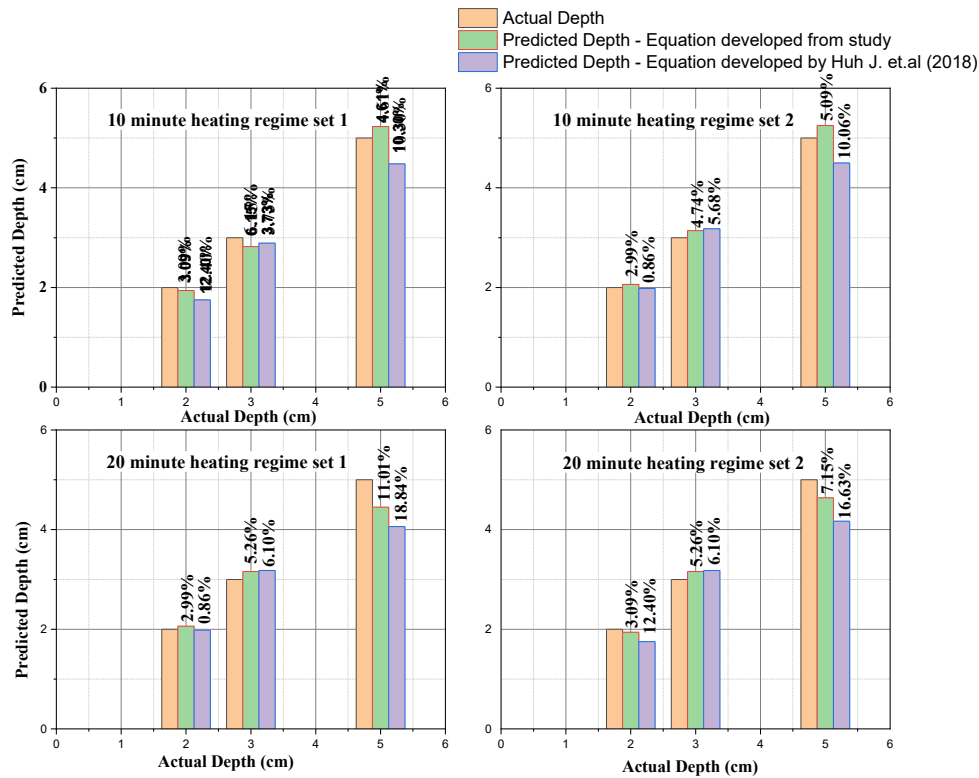


Figure 57 Comparison between the predicted depth and actual depth with respect to percentage error

It is observed from Figure 57 and Equation 13 that defect depth calculated will vary with observation time and thermal diffusivity of concrete. Hence observation time and thermal diffusivity are the two main parameters which will affect the defect depth calculation. From Figure 49 and 52 it is seen that absolute thermal contrast varies non linearly with time. The absolute thermal contrast graphs presented in this study are smoothened to fit 5th order polynomial curve. The parameters that affect thermal contrast are depth at which defect is located and time of heating. From this study it is observed that there is no change in thermal contrast when thickness of defect is changed. The thermal contrast plots are utilised to obtain observation time. There is no much change in value of observation time when heating time is changed. Hence it can be concluded that change in thickness of defect will not affect the results considerably and any duration of heating will give same result. However, the heating time

should be sufficient enough to set up required temperature gradient across the surface of slab to generate required thermal contrast.

The research data reported from finds that *Hiasa et al.*, (2017), *Cotic et al.*, (2015), *Hiasa et al.*, (2018) & *Pozzer et al.*, (2024) adopted thermal contrast method to calculate depth of defect in concrete slab. The research reported in above literature is conducted in different parts of the world like Europe and South Korea. The above researches have motivated the authors to conduct such infrared thermography experiments in this part of the world. The equation to determine the depth of internal defect in concrete in this study incorporates the nonlinear thermal behaviour of concrete which is done only in this study. This study contributes to development of defect depth detection model based on the absolute thermal contrast to enhance its applicability to different regions of the world. Global production of cement is 4.2 billion tonnes per year as per Global Cement and Concrete Association and is set to double to 9.8 billion tonnes per year by 2050. A significant portion of this is utilized for repair and rehabilitation of buildings in unplanned manner. The concrete repairs performed inconsistently will lead to frequent failure of repaired concrete, which is usually noticed. As per Gurkan et al., (2018) almost half of conventional concrete repairs fail in the field. The accurate detection of subsurface defects as outlined in this paper allows for timely maintenance and repair increasing the lifespan of concrete structures. This reduces the need for frequent reconstruction, thereby conserving resources and minimizing environmental impact. Reduction of reconstruction directly lower the carbon footprint associated with concrete production and construction activities. Construction debris is also reduced as need for disposal of demolished buildings is reduced. The technique can also be adopted for quick damage assessment survey of buildings in areas affected by natural disasters. Hence the infrared thermography to be promoted and adopted for regular monitoring of concrete structures for precise revealing of internal cracks and damaged region which will aid in deciding early repairs. This will play a crucial role in promoting sustainable building practices and contribute to sustainability of maintaining built environment.

5.6 Application of depth equation

As discussed earlier, Equation 13 developed in this study was able to predict depth of sub-surface defects with M.A.P.E. upto 5.12%. This is much lower than Equation 14 which exists in literature that uses linear correlation and predetermined factor k . The concrete slab used in this study had defects upto 5 cm depth. The accuracy of the equation to detect sub-surface defects more than 5 cm from surface is to be investigated. For this purpose, validated FEA

simulation as explained in section 5.5.3 is used. The technique developed in this study is utilised to predict depth upto 10 cm using data obtained from validated FEA simulation.

5.6.1 FEA model development

A slab of size 50 x 50 x 12 cm which is same as experimentally validated simulation is modelled using FEA software as shown in Figure 58 below.

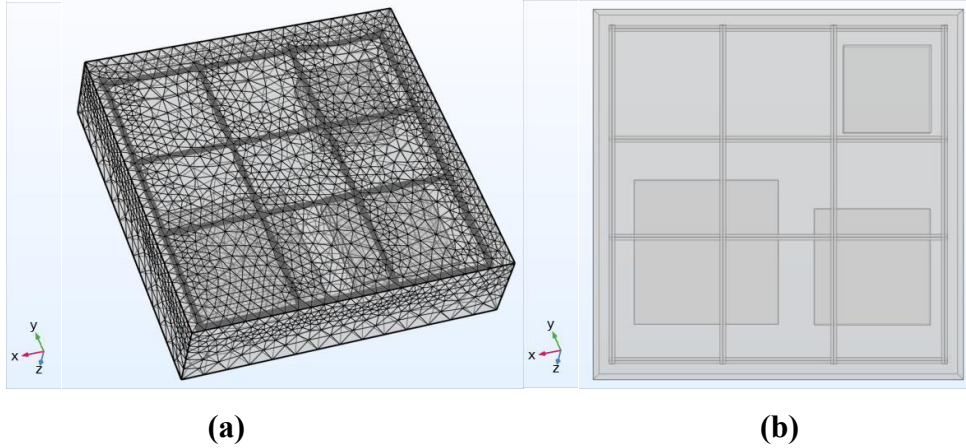


Figure 58 a) 3D Meshed FEA model b) Plan view showing defects

All the material properties and boundary conditions are kept unchanged to match the experimentally validated FEA model. The details of defects are as shown in Table 27 below.

Table 27 Sizes of defects embedded in the FEA slab model

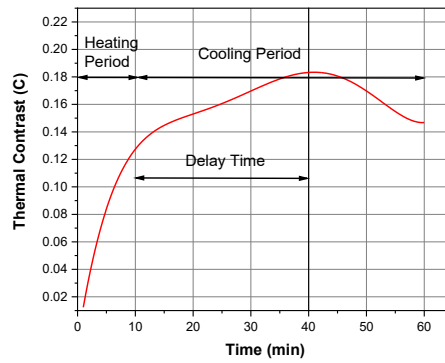
Label	Length (mm)	Width (mm)	Thickness of defect (mm)	Depth from top surface (mm)	Width to Depth Ratio (WTDR)
S1	200	200	10	100	2
S2	160	160	30	80	2
S3	120	120	50	60	2

As can be seen from Table above, the Width to Depth of ratio of all defects is kept equal to 2. This is due to the finding that those defects which are having lesser ratio are not visible in thermal images and require additional post processing techniques. The post processing of thermal images is presented in chapter 6.

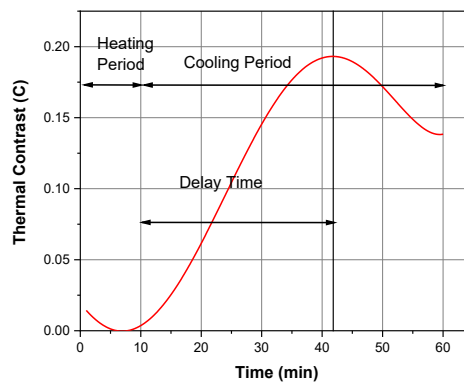
5.6.2 FEA analysis

To simulate the thermal excitation of the slab, heat flux was applied having a power 160 W which is the same as the experimentally validated FEA model. The boundary conditions are kept unchanged. The technique developed in this research is utilised to calculate depth of

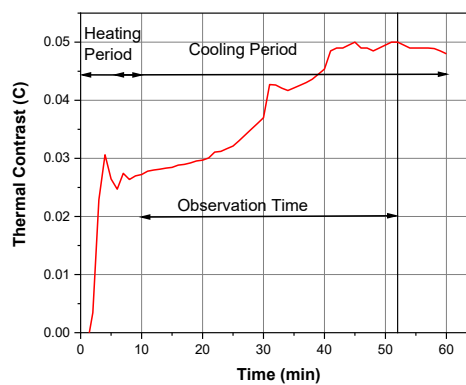
defect. The absolute thermal contrast of defects located at different depths below the surface were calculated and plotted versus time as shown in Figure 59 below.



(a)



(b)



(c)

Figure 59 Absolute thermal contrast variation a) Defect depth 6 cm (50% of total depth) b) Defect depth 8 cm (67% of total depth) c) Defect depth 10 cm (83% of total depth)

The plots above show non-linear variation of thermal contrast with time. The plots clearly show heating period and cooling period. The time gap between the phase where heating stops to the time of maximum thermal contrast is called observation time. The observation time for each depth was obtained to calculate defect depth as shown in Table 28 below. The observation time obtained was substituted in both Equation 13 and Equation 14. A comparison of actual depth with predicted depth is shown in Table 28 below.

Table 28 Comparison between the actual depth and the depth calculated using Equations 13 and 14

Actual depth of defect (D)	Delay Time or Observation Time obtained from experiment (T_{max}) (min)	Square root of Observation time and Thermal diffusivity ($\sqrt{\alpha T_{max}}$) (cm)	Depth predicted using Equation 13 (cm)	Absolute Error %	Depth predicted using Equation 14 (cm)	Absolute Error %
6	30	3.84	6.65	10.83	5.15	14.17
8	35	4.14	7.35	8.12	5.57	30.38
10	42	4.54	8.39	16.10	6.13	38.70

The M.A.P.E values for Equation 13 is 11.68% while for Equation 14 it is 27.75%. This is shown in Figure 60 below.

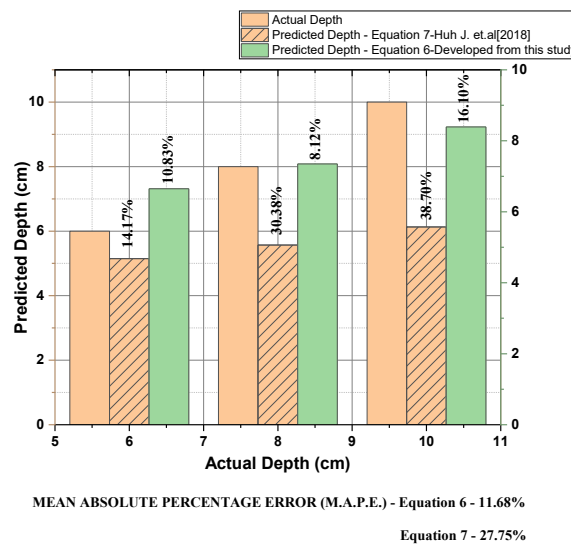


Figure 60 Comparison between the predicted depth and actual depth concerning percentage error

Therefore, depth equation developed in this research can predict depths even upto 10 cm with higher degree of accuracy than the Equation developed by *Huh et al.*, (2018).

5.7 Observations

In the present study, a reinforced concrete slab is subjected to pulsed infrared thermography. The front surface of slab was heated with an external heating source. Two different heating regimes of 10 minutes and 20 minutes were used in the experiment. The temperature profile of the slab surface was recorded using an infrared camera. The thermal contrast over the defect area is calculated for different heating regimes. The thermal contrast is used to determine the delay time or observation time for each defect depth. An equation for predicting depth was obtained by relating the depth of the defect with the observation time and thermal diffusivity of the concrete. The thermal images obtained from an infrared camera show that defects at a depth of 5 cm were not visible. The same has been verified from the thermograms obtained using FEA simulation, as shown in Figure 55 (a) and (b). For the detection of hidden subsurface defects at greater depths, there should be a sufficient temperature gradient between the subsurface defect inside the slab and the surface above the defect. As the subsurface defects in this experimental study at a depth of 5 cm had a narrower width proportional to the depth from the surface, no large temperature gradient formed on the surface when using a thermal camera. This was verified via thermography simulation via FEA. Hence, it is concluded that reliable results can be obtained for defects with depths less than 5 cm. The defects upto 8 cm depth were considered in study by *Huh et al.*, (2018). Moreover, defects with a width-to-depth ratio greater than 2 are visible only in the raw thermal images which is verified from current study. An empirical equation relating observation time and thermal diffusivity is developed taking into account non-linear thermal behaviour of concrete to predict the depth of defects. The non-linear thermal behaviour of concrete is used first time in developing relation to determine depth of damage in concrete. The depth of the defect predicted by the empirical Equation 13 developed in this research is compared with the depth obtained from the Equation 14 developed by *Huh et al.*, (2018) and is reported to have lower error. The similar study was conducted by *Pedram et al.*, (2022) who developed an equation relating depth of defect with initial temperature of slab and observation time. However the authors did not use thermal diffusivity in their approach. The thermal diffusivity of concrete is an important parameter which has been considered in this research. The equation proposed in this study can predict the depth of defects from thermograms with less error. The determination of depth of defect is important to help determine type of repair method to use. The proposed Equation No 13 can be easily used to find depth of sub-surface defects in structures monitored using thermal

scanning. The input parameters required are only thermal diffusivity of concrete and observation time which is readily available while conducting active infrared thermography scanning. The findings presented in this chapter have been documented in the publications of *Naik et al.*, (2024).

Chapter 6

Technique to identify deeper defects in concrete using post processing method

6.1 Outline of study

The Figure 61 below depicts the methodology followed to identify deeper defects in concrete slab using thermal image post processing methods.

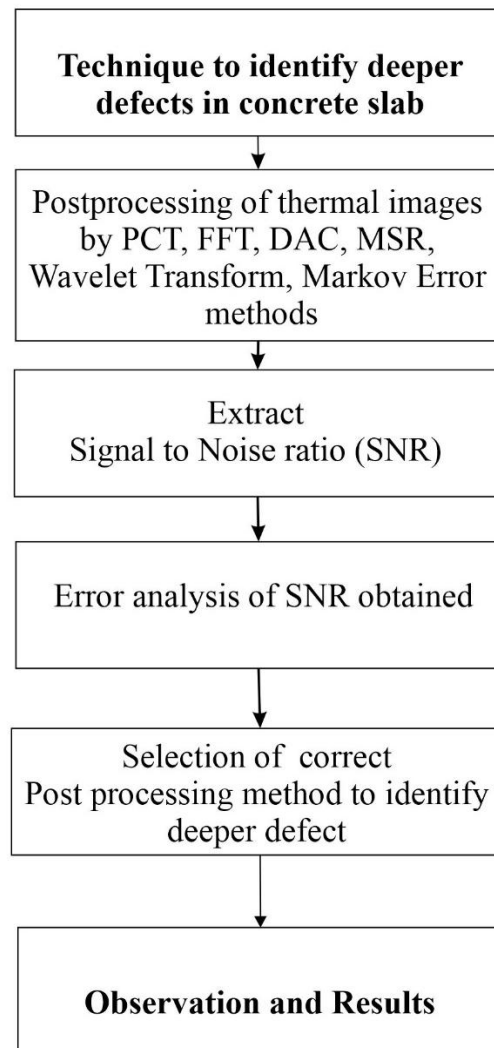


Figure 61 Flowchart of methodology to locate deeper defects in concrete by using post processing techniques

6.2 Objectives and scope

It is observed from chapter 5 that defects which are at depth of 5 cm in the laboratory cast slab are not visible in the thermal images. This is verified from FEA simulation as shown in Figure 55 in which defects D7-D9 are not visible. Hence it is proposed to perform post processing on

the recorded thermal image sequences. Many studies have utilised thermal image post processing techniques to enhance clarity of detected defects which are mentioned here. *Cotic et al., (2015)* conducted experimentation along with 3D numerical simulation on different slabs with defects of different sizes at varying depths. The thermal contrast and phase contrast method were used to develop statistical method to predict depth of defect. The authors found that it is possible to detect defects of size D at depth of $0.9D$ using thermal contrast method and $1.3D$ using phase contrast method. Defects at depths more than 6 cm could not develop thermal contrast. *Madruga et al., (2010)* used higher-order statistics (HOS) analysis to process IR images of CFRP reinforced samples and compress the information about defects into a unique image for inspection. The higher order statistics showed higher contrast ratio compared to raw thermal image and compress large amount of data sequences. *Rodríguez-Martín et al., (2015)* developed a depth prediction model by correlating surface temperature and depth of crack in welded steel. The model can be used to convert temperature values into depth values. *Moskovchenko et al., (2022)* utilized Probability of Detection (POD) function which is a function of defect size and depth for detecting defects with different size/depth ratio in 3D printed specimens. The proposed approach has been proven on raw thermographic data although many known processing algorithms, such as Thermal Signal Reconstruction (TSR), Principal Component Analysis (PCA), Pulse Phase Thermography (PPT), etc. may enhance POD. Because of a non-linear character of relationships between calculated parameters (phase, principal component) and defect parameters, this methodology requires further investigation.

Various post processing methods were applied on the recorded thermal images i.e. Principal Component Thermography (PCT), Fourier Transform (Phase and Amplitude), Multiscale Retinex, Differential Absolute Contrast, Wavelet Transform and Markov Error Contrast. They are explained in the subsequent sections. It is observed that defects at depth of 5 cm and more were visible when thermal images were processed in case of few techniques only. Hence Signal to Noise Ratio (SNR) is used as a common metric to assess detectability of defects. The methodology for post processing and calculation of Signal to Noise Ratio (SNR) of the recorded thermal images is explained in section 6.3.

6.3 Post Processing Methodology

The recorded thermal image sequence consists of arrangement of frames having a spatial resolution of $N_x \times N_y$ pixels. In order to suitably handle the thermal sequence, the individual frames can be concatenated as a three-dimensional $N_x \times N_y \times N_t$ matrix where N_t defines the total number of frames in the sequence. The number of frames is the product of total recording duration t_{acq} and sampling frequency f_s of the camera, i.e. $N_t = t_{acq}f_s$. The sampling frequency

defines a time step δt that describes the time resolution. The signal can be processed as either a two-dimensional array (image) or on a pixel-wise basis of the temperature response over time. Two-dimensional processing methods are generally qualitative as they independently process each frame with no account of temporal information. In this study, MATLAB GUI as shown in Figure 62 below is utilized to post process recorded thermal image sequences. Thermal image sequences were captured using Infrared camera. The recorded thermal sequences should in format as shown in Table 29 below before doing post processing.

Table 29 Format of 3D matrix for postprocessing

Structure name	Description	Type
A	3D datacube	double; uint8,16; integer
B	Filename	String
C	Frame-rate f_s	value described in Hertz
D	Number of frames	integer, Z
E	Total acquisition time t_{acq}	real number, R
F	Image width (pixel)	integer, Z
G	Image height (pixel)	integer, Z

It is observed that subsurface defects at depth of 5 cm are not visible in the recorded thermal image sequences. Therefore, the image sequences are converted into 3D matrix with format as shown in Table 29 above. The 3D matrix so made is processed using all the post processing methods mentioned above. The processed images are further subjected to Gaussian Low Pass filter to remove any noise due to reflection, emissivity and uneven heating. The filtered image sequence is then enhanced using Global Histogram Equalization. A program is developed using an configured algorithm to determine the SNR of defects at all three depths. The variation of SNR for different defect depths is plotted and conclusions are drawn regarding the effectiveness of each method. The Figure 62 shows the Graphical User Interface (GUI) of thermal image post processing program used in the current study. As seen in the Figure step 1 consists of inputting the thermal image sequence in the format shown in Table 29. The step 2 is selection of the suitable post processing method among many options. The step 3 involves application of a filter to remove noise or unwanted frequencies from the thermal image sequence. The step 4 involves the enhancement of the post processed image quality. In the final step the post processed thermal sequence in form of 3D matrix is exported and further processed in program to obtain Signal to Noise Ratio (SNR) as shown in Annexure B. The post processed image is exported as a '. mat' file which is standard MATLAB format. The .mat file is converted into 2D image using 'surf' command in MATLAB. The post processed

MATLAB image obtained from different methods is then compared with raw thermal image. To assess detectability of defects with different width to depth ratio, program as shown in Annexure B is utilised. The program gives Signal to Noise Ratio (SNR) over defect area of both post processed and raw thermal image. The Signal to Noise Ratio (SNR) of defects with different width to depth ratio are plotted in the form of bar graph and conclusions are drawn about effectiveness of different post processing methods.

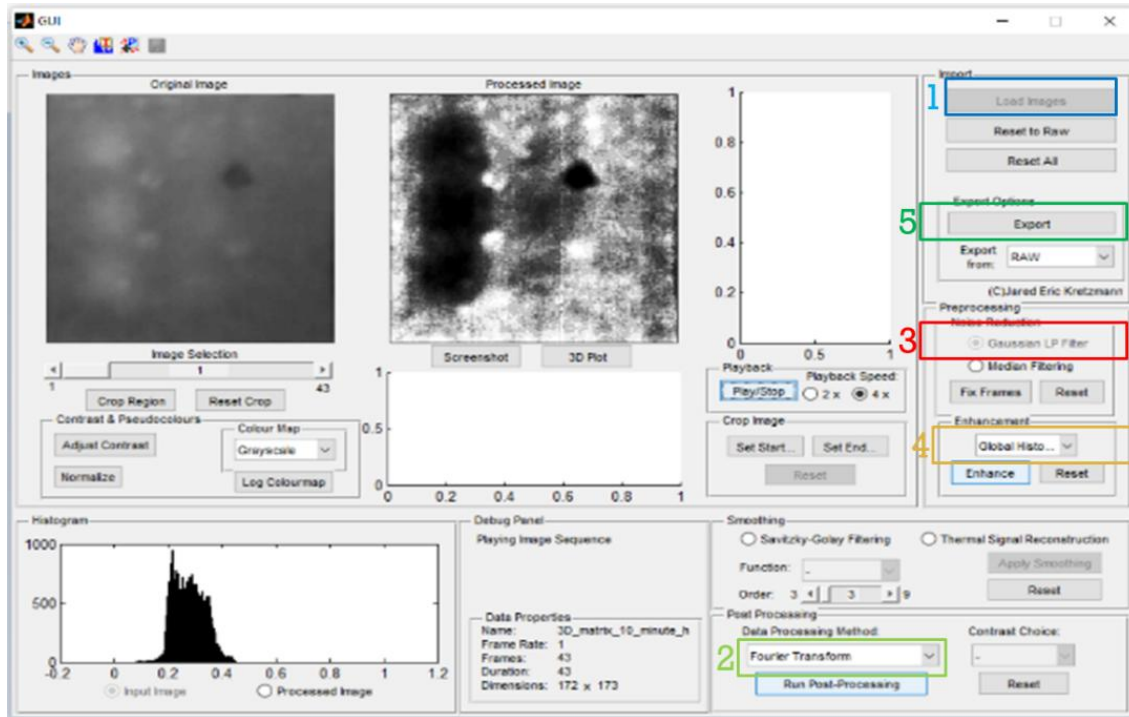
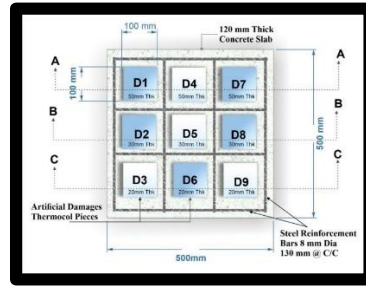


Figure 62 GUI of MATLAB post processing program

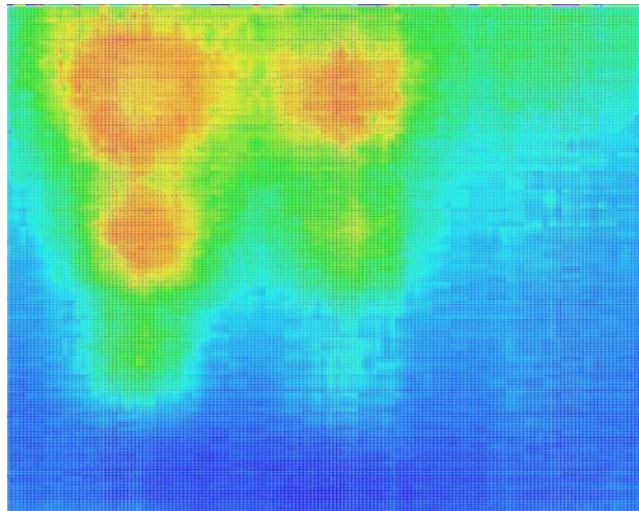
6.4 Multiscale Retinex

The multiscale Retinex (MSR) algorithm is a photometric normalization technique used by *Jobson et al., (1997)* in the field of facial recognition and has been used in X-ray photography by *Rahman et al., (2001)*. This method performed well on enhancing detail and removal of uneven-heating compared to other photometric normalization techniques. This method is seen to resemble how our eyes (retina) perceive variations in grayscale intensities. The photometric normalization is a technique of separating the image into two components, namely an illumination image containing low spatial frequencies and reflectance image containing high spatial frequencies. The high spatial frequencies represent edges and this image will present an enhanced image with higher level of detail.

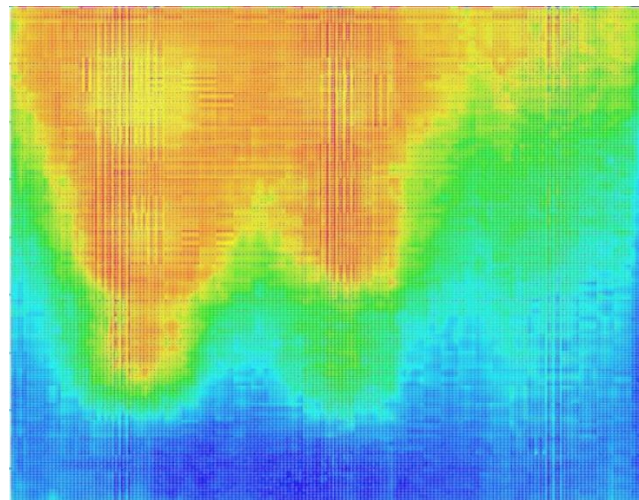
This method as explained above is applied for post processing of raw thermal images for both heating regimes. The Figures 63 & 64 below shows the raw and processed image of both heating regimes.



(a)

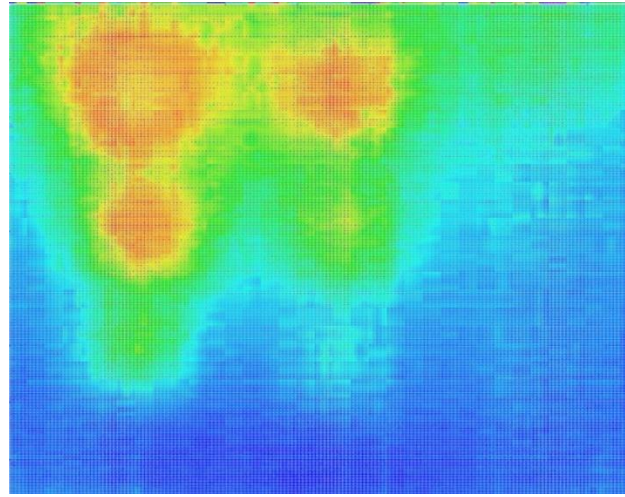


(b)

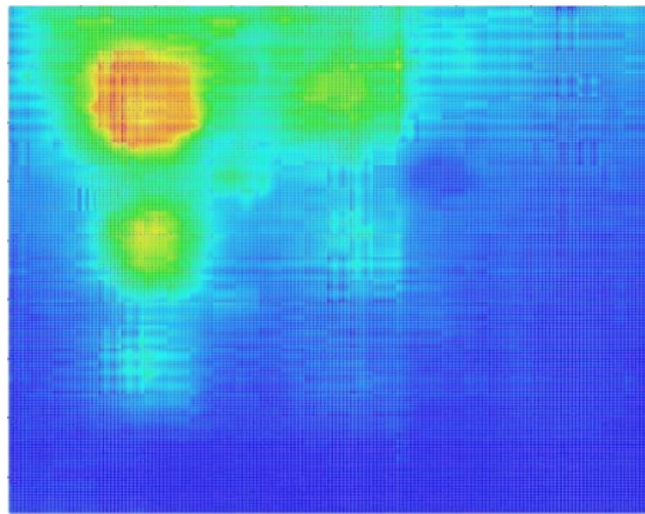


(c)

Figure 63 a) Layout of defects in slab b) Raw thermal image c) Processed image – 10 minute heating regime



(a)



(b)

Figure 64 a) Raw thermal image b) Processed image – 20-minute heating regime

It is observed from Figures 63 and 64 that contrast of defects which are already visible in raw thermal images is enhanced significantly. A comparison of SNR of defects at 5 cm depth between raw image and processed image showed that SNR has increased. An increased SNR suggests improved detectability of defects.

6.5 Differential Absolute Contrast (DAC)

The differential absolute contrast (DAC) removes the need for the manual selection of a sound area S_a . The technique was originally based on the Dirac delta function for pulsed thermography (González *et al.*, 2004), which has now been extended to step thermography. The differential absolute contrast is a form of extrapolated contrast based on the extrapolation of temperature at early times through the one-dimensional semi-infinite model at the surface $z = 0$ of the specimen. The contrast is formulated on the assumption that a sound zone is expected to follow the semi-infinite model for early times t :

$$\delta T_1(t) \approx T_{Sa}(t) \quad (16)$$

where the half-space semi-infinite model for step heating is

$$\delta T_1(t) = \frac{2Q\sqrt{t}}{e\sqrt{\pi}} \quad (17)$$

At a time t' just after heating and before an actual defect becomes visible the measured temperature at the surface of the specimen is assumed to behave as an ideal sound area Sa , i.e. $\delta T_{meas}(t') = \delta T_{Sa}(t')$. At this time the surface has not been affected by the existence of a internal defect and therefore the local temperature of a defective area is exactly the same for a sound zone. A practical assumption is made where the measured temperature δT_{meas} at t' is equal to the half-space semi-infinite model at t' (Klein *et al.*, 2008). This can be defined for a step pulse at time t' as

$$\delta T_1(t') = \frac{2Q\sqrt{t'}}{e\sqrt{\pi}} = \delta T_{meas}(t') \quad (18)$$

where $\delta T_{meas}(t')$ and t' are known measurements from the thermal data. Now Equation 18 is expressed for Q/e as:

$$\frac{Q}{e} = \delta T_1(t') \frac{1}{2\sqrt{\pi t'}} \quad (19)$$

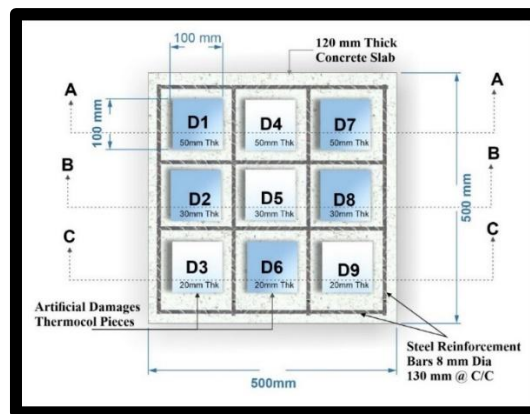
Substituting Q/e into Equations 16 and 17, the extrapolated temperature of a sound area is defined as

$$\delta T_{Sa}(t) \approx \sqrt{\frac{t}{t'}} \delta T_{meas}(t') \quad (20)$$

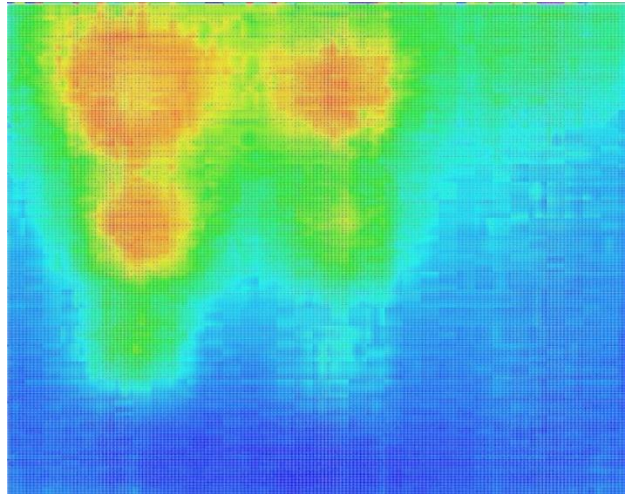
Using the absolute contrast definition, the extrapolated thermal contrast is defined using the difference of the measure temperature $\delta T_{meas}(t)$ and extrapolated temperature $\delta T_{Sa}(t)$:

$$\delta T_{DAC}(t) = \delta T_{meas}(t) - \sqrt{\frac{t}{t'}} \delta T_{meas}(t') \quad (21)$$

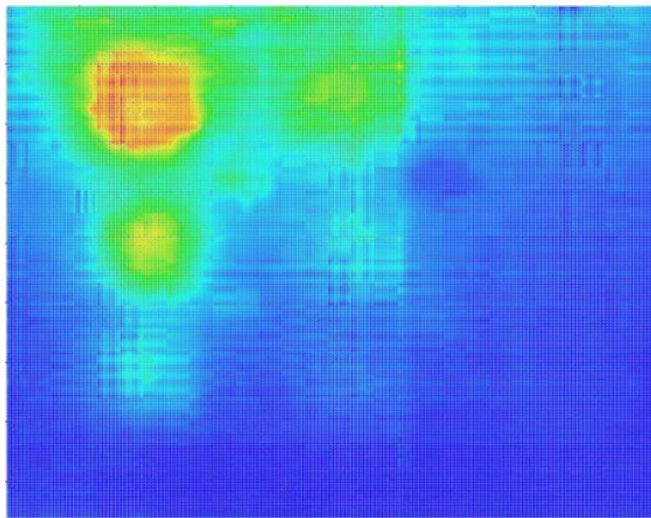
The DAC method is only valid for early times as at later times the thermal response of both the sound and defective areas deviate from the semi-infinite model where $\delta T_1(t) \neq \delta T_{Sa}(t)$. The Figures 65 & 66 below show raw thermal image and processed image of both heating regimes.



(a)

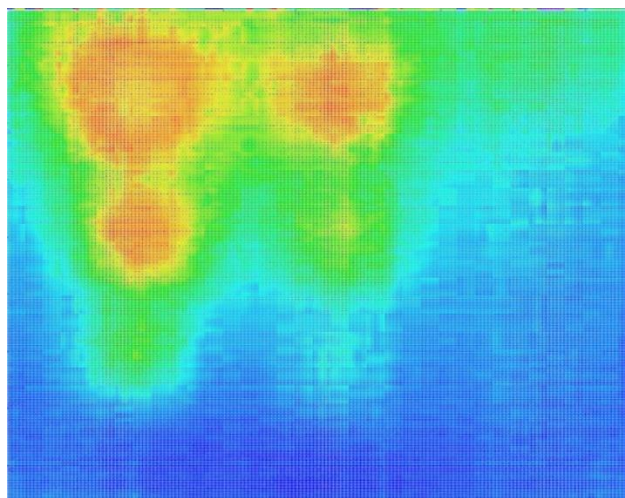


(b)

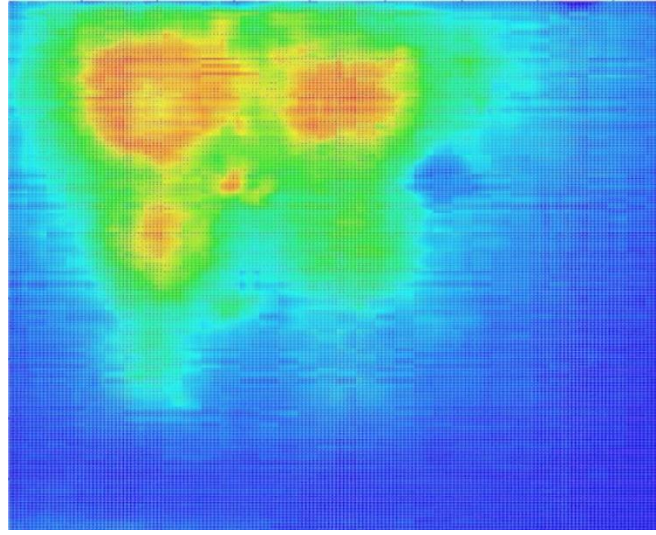


(c)

Figure 65 a) Layout of defects b) Raw thermal image c) Processed image – 10-minute heating regime



(a)



(b)

Figure 66 a) Raw thermal image b) Processed image – 20-minute heating regime

The Figures 65 and 66 shows that processing of thermal image by using DAC does not enhance quality of thermal image. Hence DAC is not much of an effective method in detection of deeper defects in concrete.

6.6 Markov Error Contrast

The Markov error contrast is defined as the error between the actual and an estimated temperature for each individual pixel's time sequence (*Larson, 2011*)

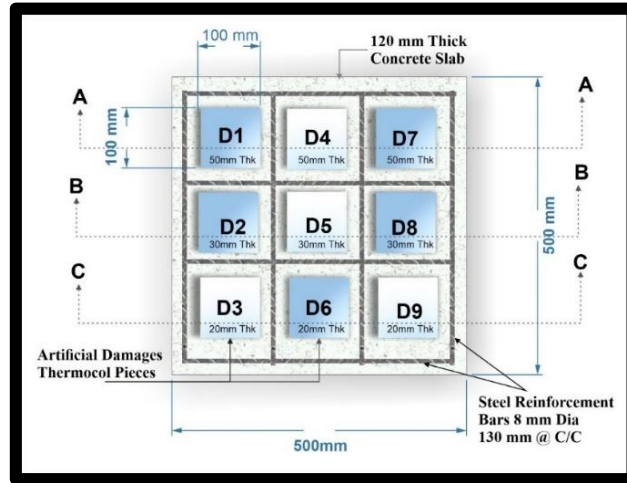
$$E(t) = T(t) - T_{est}(t) \quad (22)$$

The Markov error contrast is based on a Markov chain treating each temperature in the pixel's time sequence as independent. To evaluate the error at time t an estimated temperature is required at the same time. Thus, the estimated temperature can be calculated as a function of the previous temperature in time and repeated until each temperature has synthetically been reconstructed. Using a simplified one-dimensional response for step heating the estimated temperature can be evaluated. In this case the Markov error will represent and amplify any deviation from an ideal sound area S_a response. The estimated temperature can therefore be calculated by using a modified version of Equation 23:

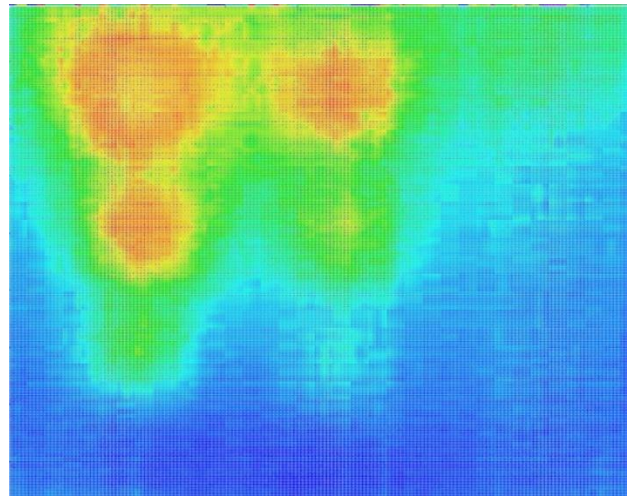
$$T_{est} = T(t-1) * \sqrt{\frac{t-1}{t}} \quad (23)$$

where $T(t-1)$ is the previous temperature at a current time t in thermal sequence.

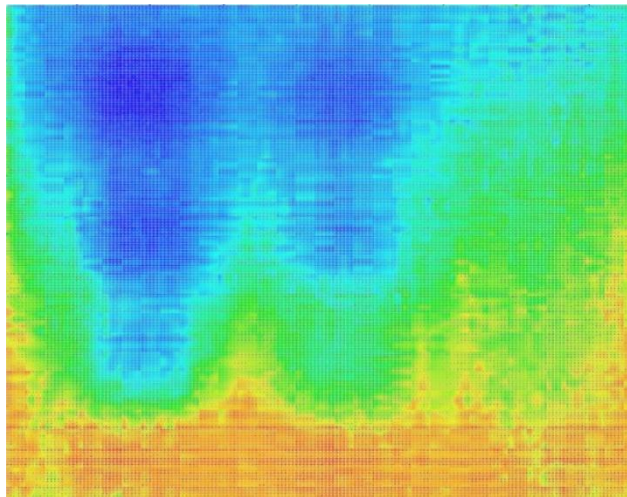
Markov Error contrast is applied on the raw thermal images. Figure 67 & 68 below shows raw thermal image and processed image.



(a)

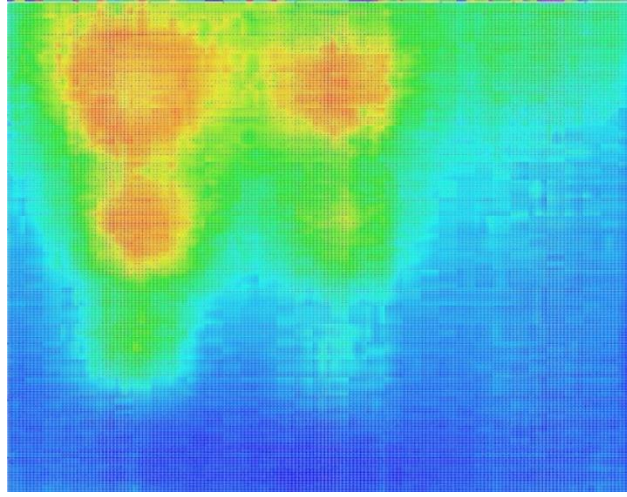


(b)

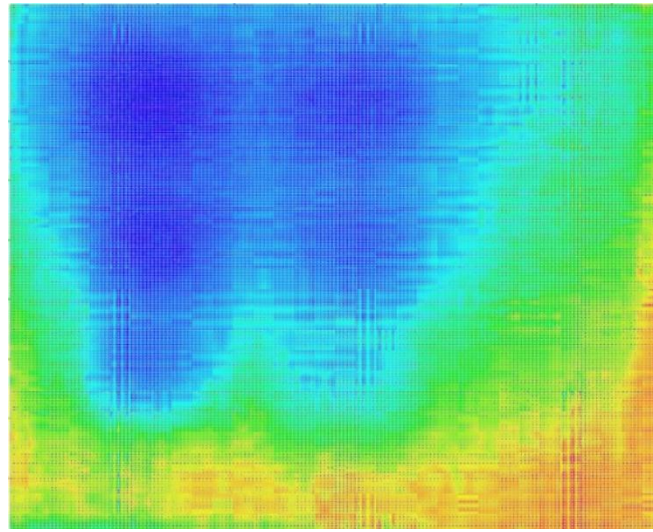


(c)

Figure 67 a) Layout of defects b) Raw thermal image c) Processed image – 10-minute heating regime



(a)



(b)

Figure 68 a) Raw thermal image b) Processed image –20-minute heating regime

The Figures 67 and 68 show that defect and sound region intensities got interchanged. In raw thermal image the hotter regions are yellow and cooler regions are blue. This gets reversed after using Markov Error contrast method.

6.7 Fourier Transform

The one-dimensional discrete Fourier transform is applied to the temperature history of each pixel $T(t)$ as (Ibarra-Castaneda, 2005)

$$F_k = \delta t \sum_{n=0}^{N-1} T(n\Delta t) \exp^{-j2\pi nk/N} \quad k \in \mathbb{Z} \quad (24)$$

where $j_2 = -1$, $n = (0, 1, 2, \dots, N - 1)$ defines the next sampling time for N sample points separated by a sampling interval δt and k designates the frequency increment ($k = 0, 1, 2, \dots, N$). The Fourier transform is defined to cover infinite frequencies but considering that there is a finite number of time samples defined by the signal of length N_t , the number of frequencies needed to adequately represent the signal is $N \geq N_t$. Because the signal is non-periodic, the

signal is typically zero-padded and in this case $N \approx 2Nt$ which provides enough sampling frequencies.

The complex exponential term of the Fourier coefficients produces a real and complex term, $F_k = Re_k + jIm_k$, which can be separated to produce discrete amplitude A and phase ϕ data:

$$A_k = \sqrt{Re_k^2 + Im_k^2} \quad (25)$$

$$\phi = \tan^{-1} \frac{Im_k}{Re_k} \quad (26)$$

The resulting one-dimensional amplitude and phase data can be separately reshaped to produce a series of amplitude and phase images. The amplitude and phase signal produces frequencies ranging from f_1 to f_N in Hz as illustrated in Figure 69. The number of discrete frequency samples correspond to the number of discrete time samples N . However, only half of the frequencies needs to be considered as the amplitude and phase images are symmetrical about frequency $f_{N/2}$. The available frequency components do not represent 'real' frequencies but can be calculated directly from the time domain as (Maldague & Galmiche, 2001)

$$f = \frac{n}{N\delta t} \quad (27)$$

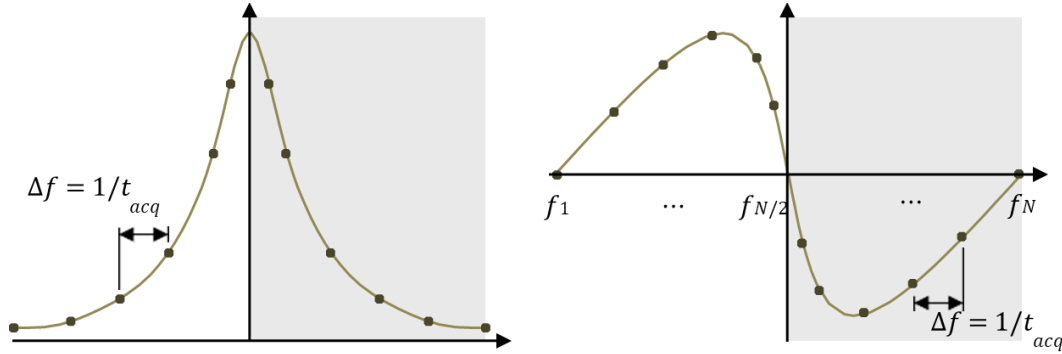
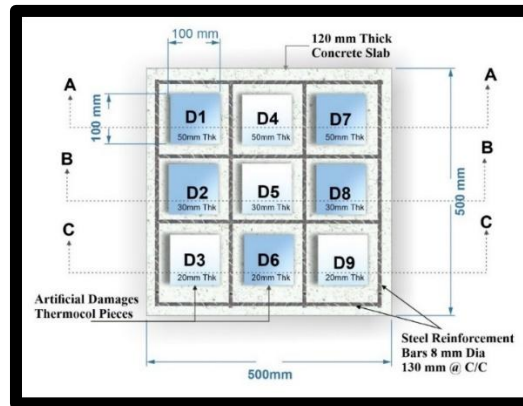


Figure 69 Amplitude (left) and phase (right) profiles produced by the Fourier Transform on a pixel's temperature response (adapted from Ibarra-Castanedo, 2005)

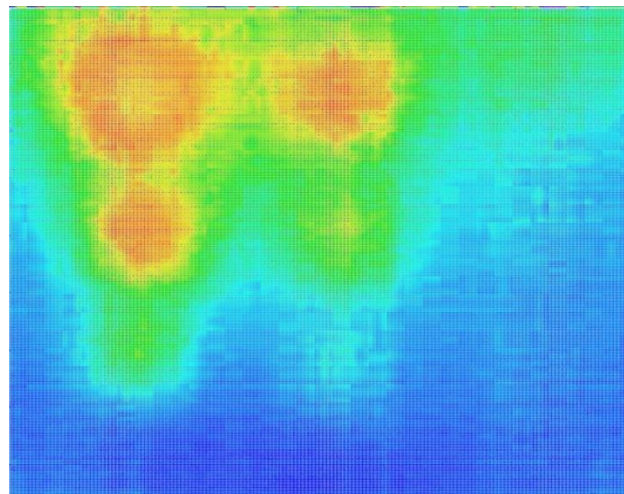
Generally, the Fourier transform can be performed with little attention to the data, however under-sampling and poorly truncated data has an effect on the performance of the transform in defect estimation methods (Ibarra-Castanedo, 2005). Poorly defining the data truncation window, i.e. the beginning and end of the thermal sequence after all defects have emerged, affects the overall frequency resolution. An increase in error was observed for depth estimation for a smaller truncation window in pulsed thermography. The FFT computation assumes the signal is periodic. In the case of transient thermography, the signal satisfies the periodic requirement as the signal starts at zero at the beginning of the time window and then rises to some maximum and decays again to zero before the end of the time window. This can be seen

as a quarter wave of a periodic signal and presents no sharp changes. However, the square pulse temperature response produces a sharp change between the heating and cooling phases which may reduce the effectiveness of this method.

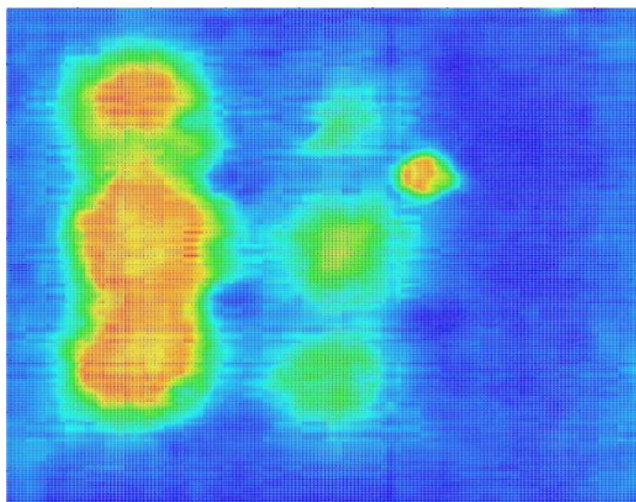
As explained earlier Fourier Transform of raw thermal image gives phase image as well as amplitude image. Figure 70 & 71 below shows the raw thermal image and phase image obtained using Fourier Transform.



(a)

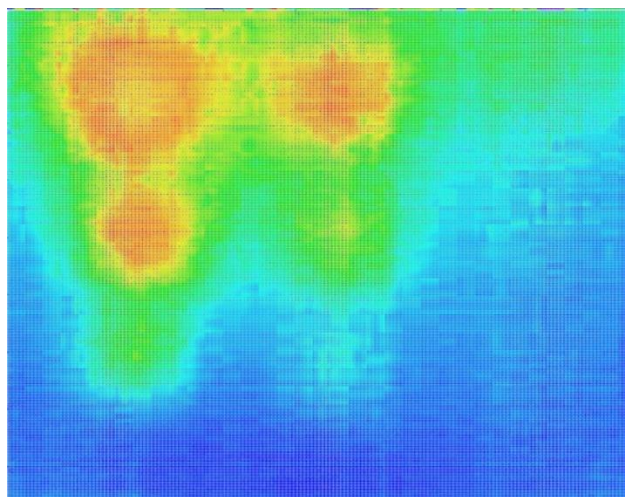


(b)

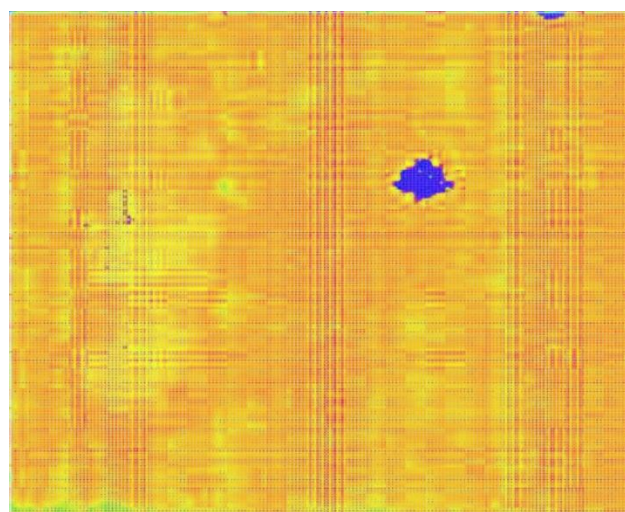


(c)

Figure 70 a) Layout of defects b) Raw thermal image c) Phase image – 10-minute heating regime



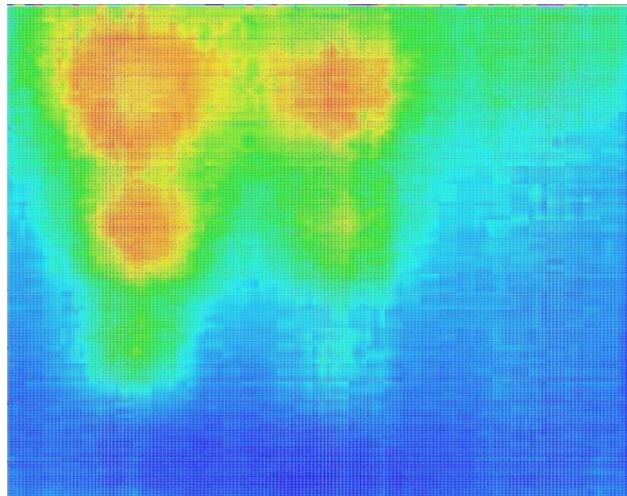
(a)



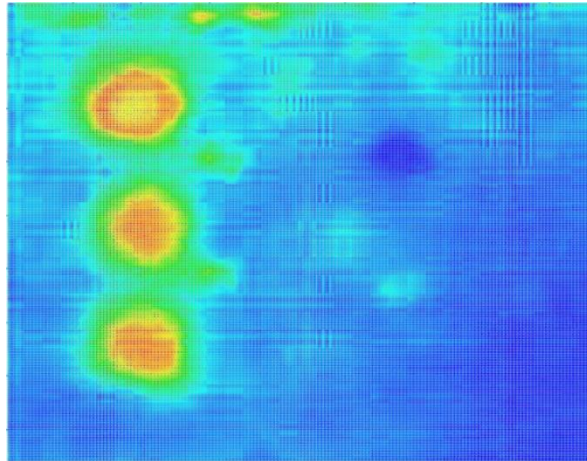
(b)

Figure 71 a) Raw thermal image b) Phase image – 20-minute heating regime

Figures 72 & 73 below shows the raw thermal image and amplitude image obtained after doing Fourier Transform.

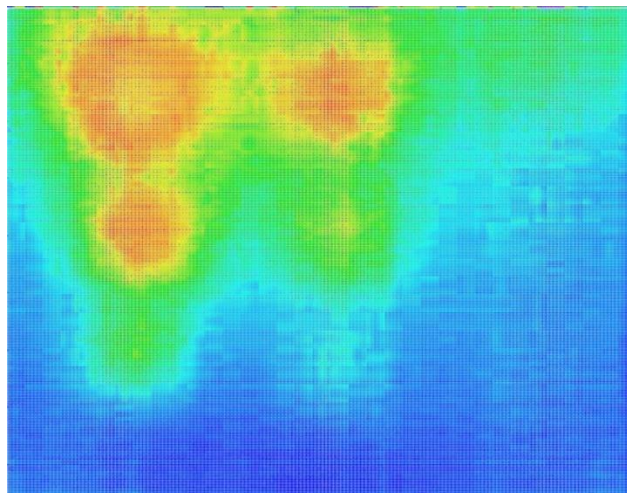


(a)



(b)

Figure 72 a) Raw thermal image b) Amplitude image – 10-minute heating regime



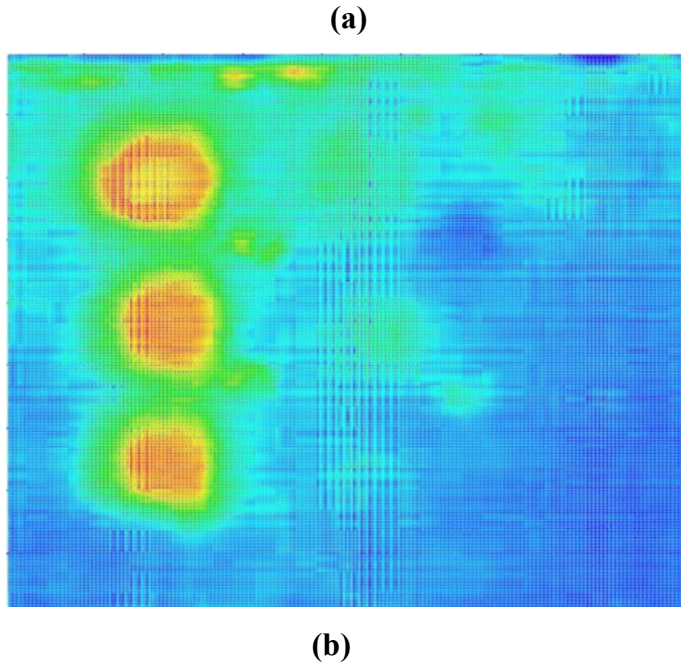


Figure 73 a) Raw thermal image b) Amplitude image – 20-minute heating regime

It is observed from Figures 70 to 73 above that phase images improve detectability of defects at deeper depths as compared to amplitude images. This is verified in graph showing comparison of SNR values. The amplitude images are found to improve detectability of defects at shallow depths.

6.8 Wavelet Transform

The wavelet transform is the extension of the Fourier transform with the added benefit of preserving time information since defect depth is a function of the square root of time. Instead of decomposing the signal by a continuous sinusoidal function, as in the Fourier transform, the signal is decomposed through window functions containing a periodic waveform of limited duration, known as a wavelet. The basic wavelet transform can be seen as the convolution of the signal $f(t)$ and daughter wavelet $\psi_{STr}(t)$ defined for a translation factor T_r and a scale factor S :

$$W_f(S, T_r) = \int_{-\infty}^{\infty} f(t) \psi_{STr}(t) dt \quad S, T_r \in \mathbb{R} > 0 \quad (28)$$

The daughter wavelet $\psi_{STr}(t)$ is expressed as a scaled and translated replica of a single base wavelet called the mother wavelet $\psi_m(t)$:

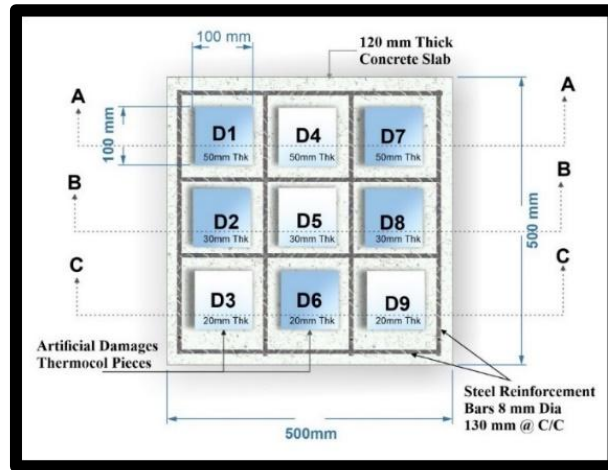
$$\psi_{STr}(t) = \frac{1}{\sqrt{S}} \psi_m \left(\frac{t - T_r}{S} \right) \quad (29)$$

where the scaling factor S controls the width of the wavelet and the translation factor T_r controls the position of the wavelet along the analysed signal. The choice of the wavelet for thermographic analysis is desired to share the characteristic qualities of the Fourier transform and, hence, the complex Morlet wavelet is chosen as the mother wavelet (*Galmiche &*

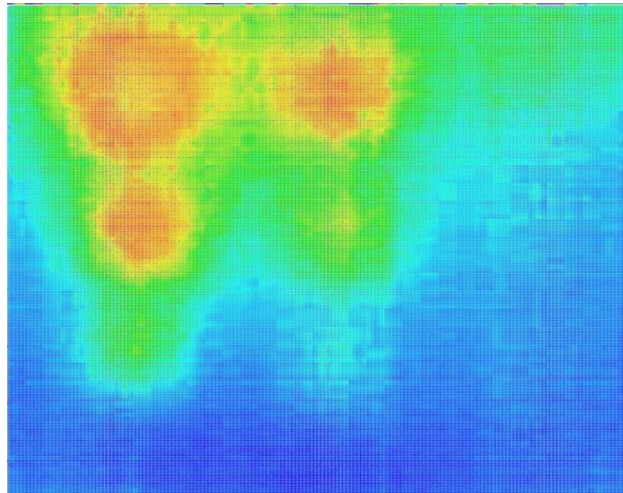
Maldague, 2001). The wavelet transform can be implemented using the fast Fourier transform (FFT) which conveniently handles the time-shift parameter, Tr , and the convolution can efficiently take place in the frequency domain - the convolution theorem states that convolution in time domain corresponds to multiplication in frequency domain. The simple multiplication of the signal and daughter wavelet can be computed and repeated for multiple scales:

$$W_f = IFFT[FFT(f(t)) * FFT(\psi_s(t))] = Re_s + jIm_s \quad (30)$$

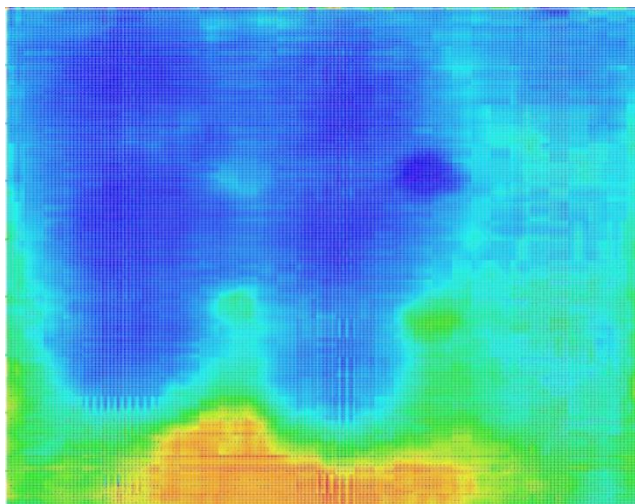
where the translation factor Tr is controlled by the FFT algorithm and reiterated for scales $S > 0$. The inverse fast Fourier transform, IFFT, is performed to produce the real and complex parts to extract the amplitude and phase data for each scale S . The wavelet transform produces two-dimensional time-scale data from a one-dimensional temperature signal. Even though the fast Fourier transform is relatively efficient, the wavelet transform is computational expensive and requires a considerable number of computations and storage. Figure 74 & 75 below shows raw thermal image and image processed using Wavelet Transform as explained earlier.



(a)

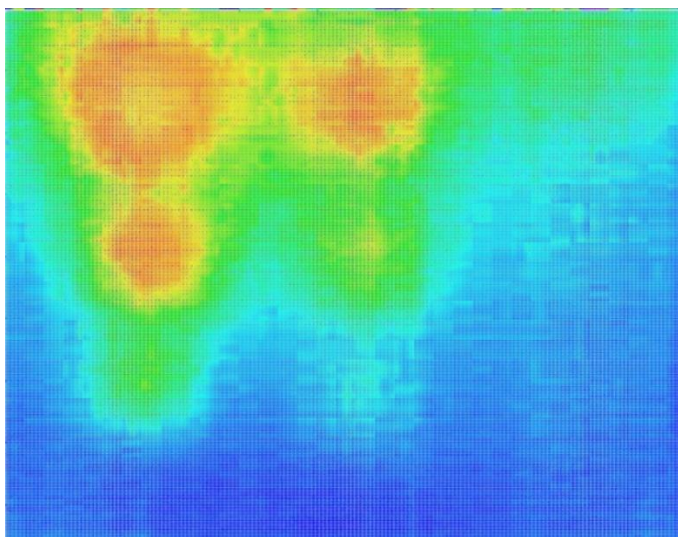


(b)

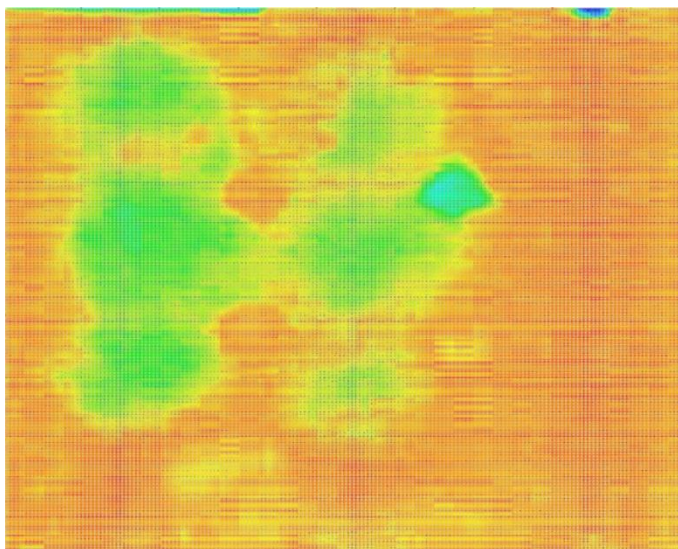


(c)

Figure 74 a) Layout of defects b) Raw thermal image c) Processed image –10-minute heating regime



(a)



(b)

Figure 75 a) Raw thermal image b) Processed image –20-minute heating regime

From Figure 74 and 75 it is seen that usage of Wavelet Transform introduces lot of noise and non-uniformity in the raw thermal images. However, it increases the SNR of those defects that are not visible in raw thermal images.

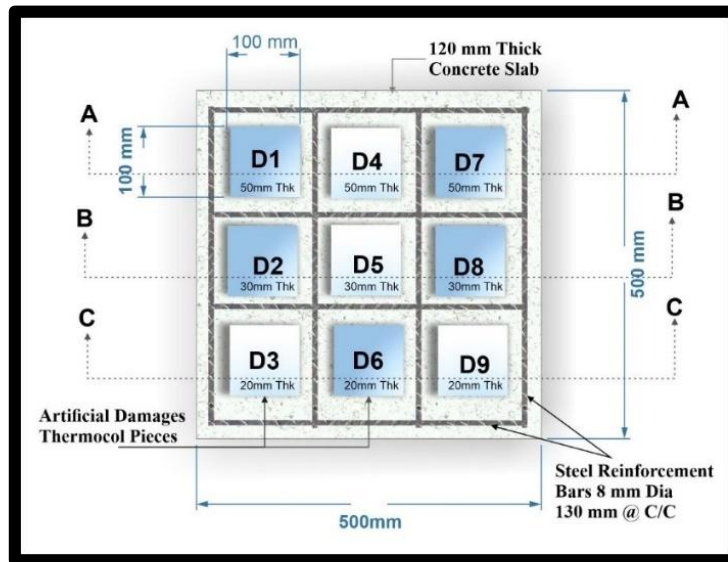
6.9 Principle Component Thermography

The Fourier transform is a convenient way of decomposing the thermal signals to the phase-frequency space through a set of sinusoidal basis functions, however transient signals are not periodic signals, particularly in the case of square pulse heating. Sinusoidal functions indeed may not be the best choice for representing either transient heating signals. Principal component thermography (PCT) is based on an eigenvector transform which applies an orthogonal transformation to the thermal inspection data. PCT relies on singular value decomposition (SVD) which closely matches principal component analysis and are both used to reduce high-dimensional data into fewer dimensions while retaining relevant information. The only difference is that there is no need to calculate the covariance matrix which can lead to numerical rounding errors when evaluating the eigenvalues. Eigenvectors can be portrayed as axes along which a linear transformation acts by simple compression or stretching of data on orthogonal axes. Since eigenvalues are orthonormal, they represent a complete description of the spatial and temporal variability in the entire thermal sequences as a smaller set of orthogonal statistical modes. Assuming that the thermal data is a $M \times N$ data matrix A ($M > N$), then the SVD can be applied as follows (*Marinetti et al., 2004*):

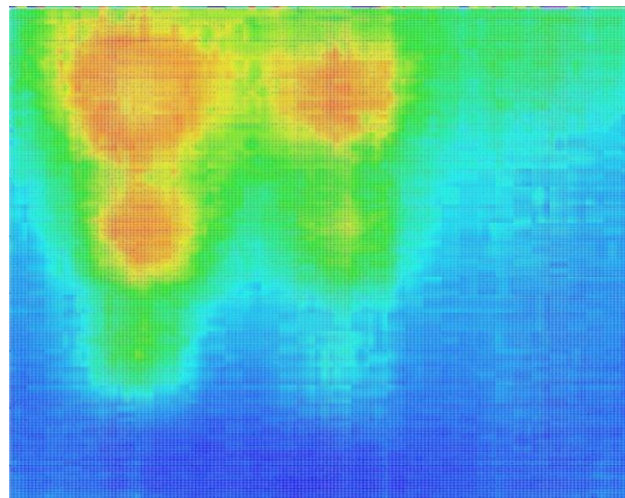
$$A = URV^T \quad (31)$$

where U is a $M \times N$ matrix, R is a diagonal $N \times N$ matrix containing the absolute values of the eigenvalues (singular values) of A and V^T is an $N \times N$ unitary matrix. In order to apply this to the thermal data-cube matrix, the total number of pixels are rearranged into a single vector to condense the information as a single matrix A having dimensions $(N_x \times N_y) \times N_T$ with time along the columns. The first few EOFs describe the largest variability in the thermal sequence and generally only a few EOFs contain useful images. Furthermore, orthogonal statistical modes describing time variations are present in the rows of VT known as principal components (PCs). The PCs cannot be displayed as an image but have been proposed to allow defect depth estimation. This requires isolating the defective region and performing SVD separately on each identified defect. Not much work has been performed to show the accuracy of this estimation which is also an inversion method requiring knowledge of thermal diffusivity.

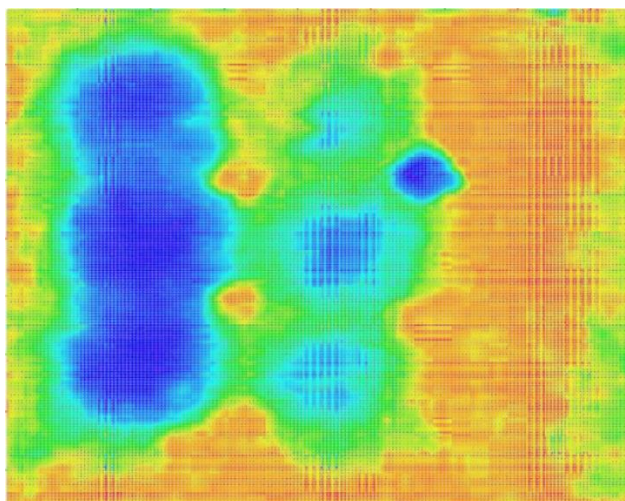
Figures 76 and 77 compare a thermal image captured by an infrared camera with a image post-processed using Principle Component Thermography (PCT).



(a)

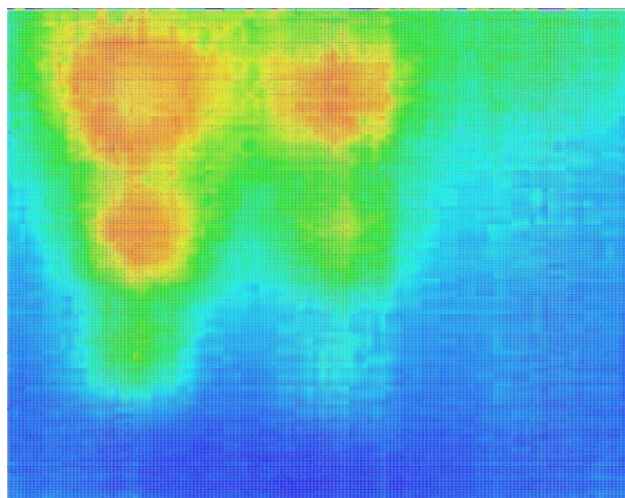


(b)

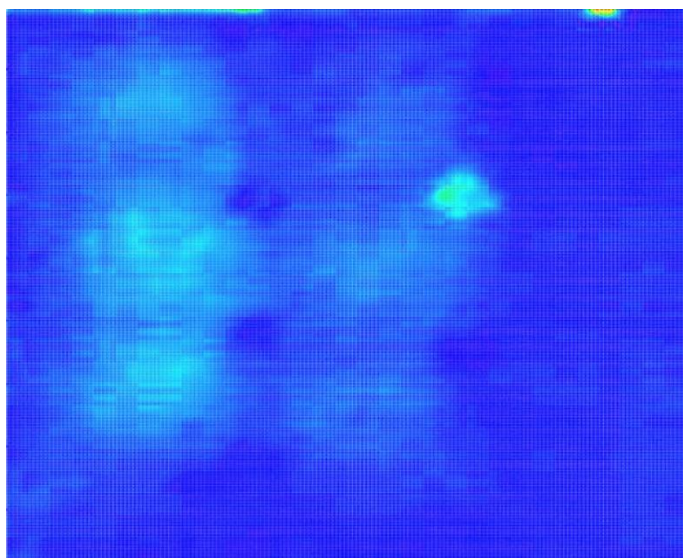


(c)

Figure 76 a) Layout of defects b) Raw thermal image c) Processed image –10-minute heating regime



(a)



(b)

Figure 77 a) Raw thermal image b) Processed image –20-minute heating regime

From Figure 76 and 77 it is seen that usage of PCT enhances the defects and increases contrast in the raw thermal images. However, it increases the SNR of those defects that are not visible in raw thermal images.

6.10 Spatial Noise Reduction

Thermograms are prone to ambient and inherent camera noise. There are many ways to de-speckle or de-noise an image using linear, non-linear or even statistical operators. Linear filters are less preferred as they generally blur detail in the images. Gaussian low-pass filter which is a non-linear filter technique is used in the present work for reducing spatial noise.

6.11 Histogram Equalization

Histogram equalization (HE) is a common image processing technique of adjusting image contrast by redistributing the intensities of the image's histogram. HE allows the most frequent intensities to be redistributed to other intensity levels enabling lower frequency intensities such as the defect intensities to gain increased contrast. Modified HE methods have built on the classical HE method to reduce oversaturation and maintain finer detail in the image. The definitions for modified HE methods can be found elsewhere (*Park et al., 2008*).

6.12 Signal to Noise Ratio

The post processed images were extracted. The defects that were not visible in raw thermal images were slightly visible in post processed images of a few techniques. Hence SNR ratio was used as a metric to assess detectability of defects. A specially developed program was utilised for this purpose. The program is as shown in Annexure B. The Signal to Noise Ratio, (SNR), is a metric used to characterize image quality. In this section we describe a method to calculate and characterize the signal to noise ratio as per *Rose* who applied it for inspection of radiographs. SNR is defined as the reciprocal of the coefficient of variation i.e. it is the ratio of the mean to the standard deviation of a signal.

$$SNR = \frac{\mu}{\sigma} \quad (32)$$

Here, μ is the signal mean and σ is the standard deviation of the noise. SNR values of the defects at different depths of raw thermal images and post processed images are presented in the form of bar graphs as shown in Figure 78 to 83 below. The graphs are for both heating regimes used in this study.

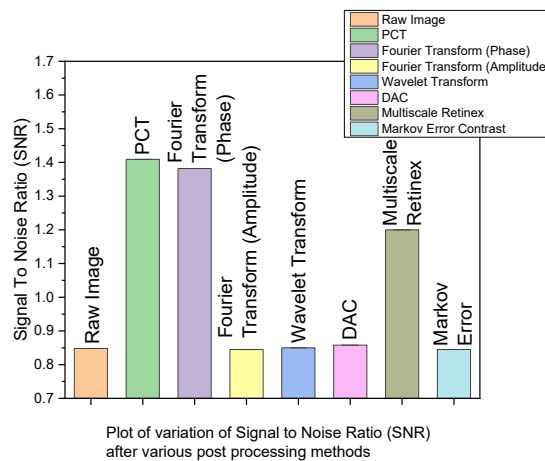


Figure 78 Plot of variation of SNR for defects at depth of 5 cm subjected to 10 minute heating regime

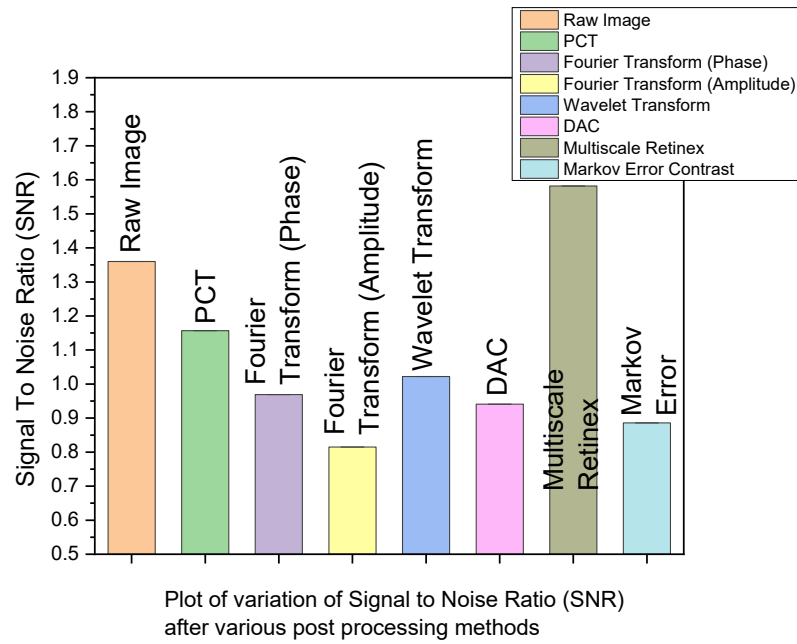


Figure 79 Plot of variation of SNR for defects at depth of 3 cm subjected to 10 minute heating regime

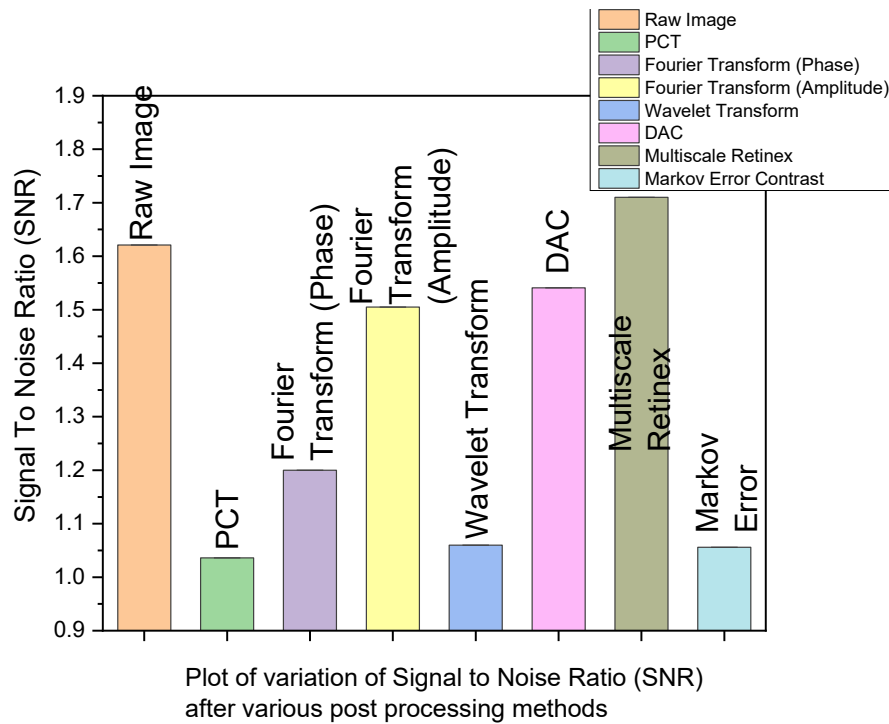


Figure 80 Plot of variation of SNR for defects at depth of 2 cm subjected to 10 minute heating regime

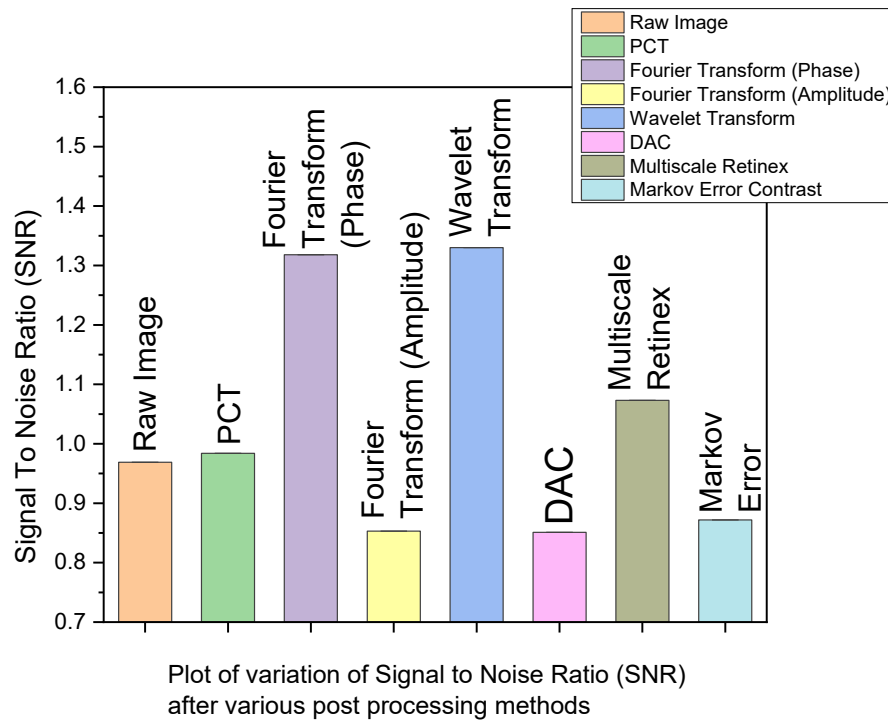


Figure 81 Plot of variation of SNR for defects at depth of 5 cm subjected to 20 minute heating regime

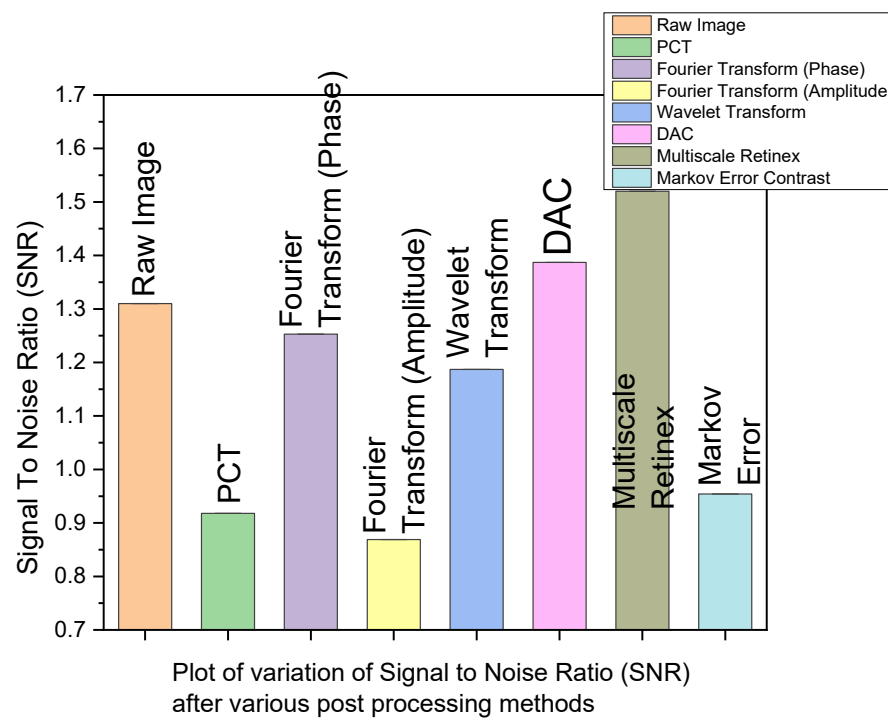


Figure 82 Plot of variation of SNR for defects at depth of 3 cm subjected to 20 minute heating regime

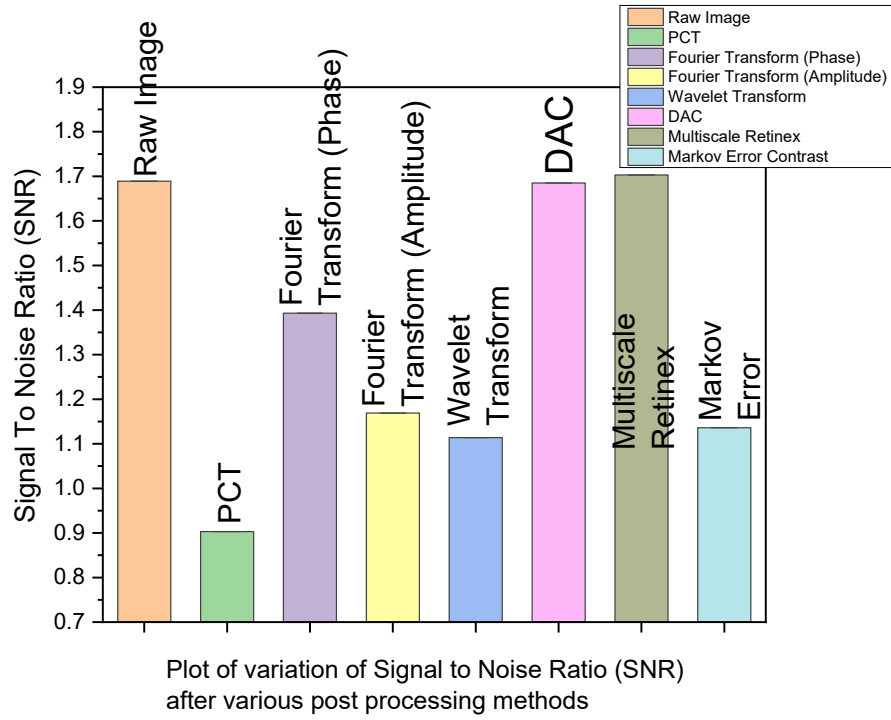


Figure 83 Plot of variation of SNR for defects at depth of 2 cm subjected to 20 minute heating regime

From above Figures 78 to 83 it is observed that for defects at depth of 5 cm, SNR variation is highest after Fourier Transform (Phase) method is performed on raw thermal images. It is also observed that for defects at depth of 2 and 3 cm SNR variation is highest after Multiscale Retinex method is performed on raw thermal images.

6.13 Observations

In earlier chapter, raw thermal image sequences captured using infrared camera were analysed using absolute contrast method. Thermal contrast was plotted versus time and equation to predict depth was derived considering non-linear behaviour of thermal contrast. The derived equation could predict defect depths upto 10 cm more accurately than equations existing in literature. However, it is observed from raw thermal images that defects at 5 cm depth were not visible. Hence the raw thermal image sequences were subjected to various post processing techniques as explained above in this chapter.

It is observed that defects are visible in the raw thermal images if Width to Depth ratio (WTDR) is more than 2. It was found that defects that are not visible in raw thermal images are visible only in images produced by few post processing methods. Hence Signal to Noise Ratio (SNR) as explained above is used to measure as a common metric to assess detectability of defects. It can be seen that irrespective of heating period, Fourier Transform (Phase) method lead to increase in detectability of defects that are not visible in raw thermal image. It is also

found that Multiscale Retinex method improves detectability of defects that are visible in raw thermal images. Other post processing methods introduce noise and non-uniformity in thermal images and hence distort visibility of already visible defects. More studies can be performed by performing multiple post processing methods on raw thermal image sequences.

Chapter 7

Comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) (Experimental verification)

7.1 Outline of study

Figure 84 below explains the process of comparison between infrared thermography and ultrasonic pulse echo (UPE) method.

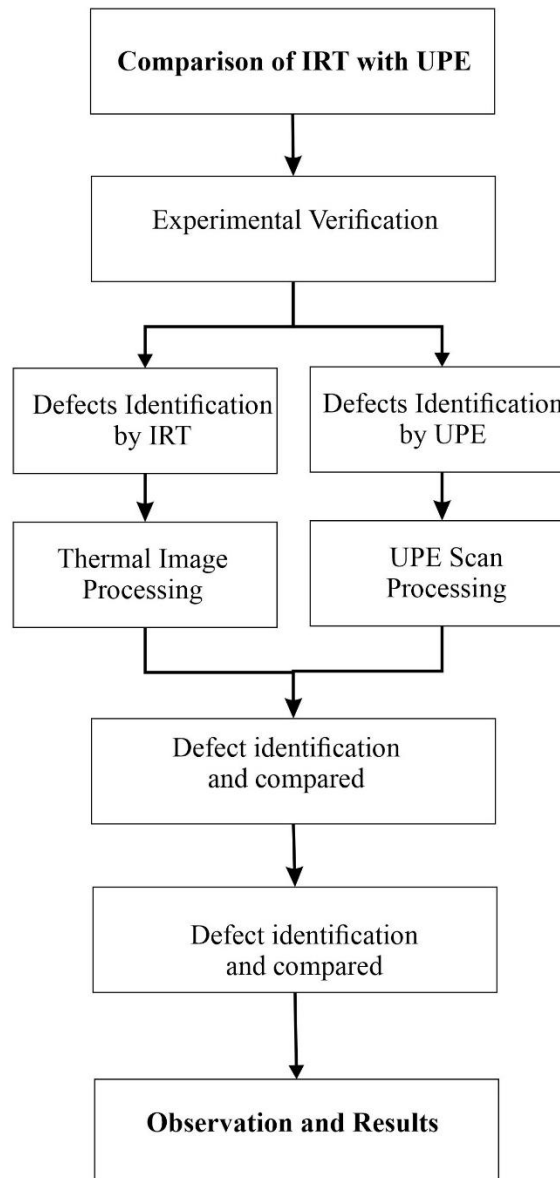


Figure 84 A flowchart of methodology to compare infrared thermography and ultrasonic pulse echo (UPE) method

7.2 Objectives and Scope

The chapters 3 to 6 have focused on application areas of infrared thermography to inspect buildings. The application areas considered in these chapters are the calculation of defect area, defect depth and identification of deeper defects using post processing methods. This chapter compares the Ultrasonic Pulse Echo (UPE) method with Infrared Thermography. Both methods were applied to detect sub surface defects in a single concrete slab. The results of both methods are compared. This work aims to evaluate the usefulness and precision of infrared thermography with Ultrasonic Pulse Echo (UPE) method in detecting defects inside concrete slab. The UPE method involves sending ultrasonic pulses into the structure which is to be inspected. Whenever an ultrasonic pulse encounters two different layers of different acoustic impedance, a part of the pulse gets reflected. The reflected pulse which involves acoustic waves is detected by the receiver (Janku et al., 2019). The UPE method can be applied to determine the thickness of concrete members with one side access, detect sub-surface defects and voids as well as to verify location of grouting defects. However unlike infrared thermography which is non-contact scanning technique, UPE requires proper coupling to the surface to be tested. Also, the UPE scans require correlation with visual images.

7.3 Experimental setup

To conduct UPE scan measurement PUNDIT PD 8050 machine manufactured by Swiss company Proceq is used. The instrument is shown in Figure 85 below.



Figure 85 Pundit PD 8050 for CT scanning of concrete slab

The UPE scan is performed in presence of professionals from Kaizad Engineer firm located in Vadodara, Gujarat. The instrument can perform line scan (2D scan), full matrix 3D scan

and grid scan. PD8050 uses ultrasound pulse echo technology, in which both the transducers and receivers are on the same side of test object. This can detect objects with a different acoustic impedance, such as cracks, delaminations, rebars, honeycombs, etc. The instrument has 3 rows of 8 transducers which is in total 24 transducers. A channel is a group of transducers operating together. The Pundit has 8 channels: the 3 transducers in the same column are connected in parallel as shown in Figure 86.

8 channels

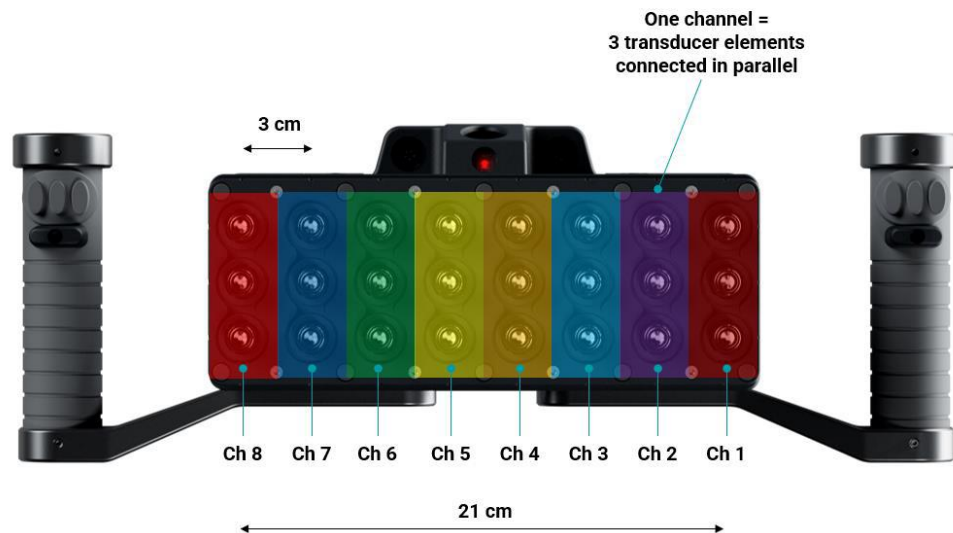


Figure 86 Eight channels of Transducers (Source: Proceq SA)

A single channel transmits echoes which are received by the other seven channels. Each channel transmits in turn as shown in Figure 87.

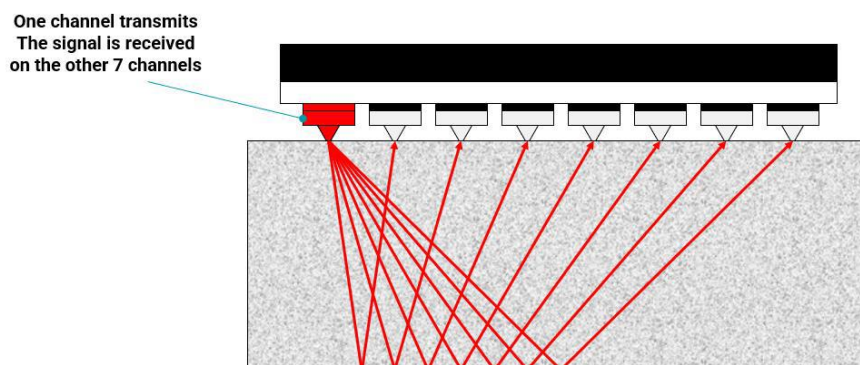


Figure 87 Signal emitted by one transducer picked up by other transducers (Source: Proceq SA)

The experiment is conducted on the concrete slab cast for infrared thermographic inspection. The Figure 88 shows working of Ultrasonic Pulse Echo machine. The transducers emit signal

which is picked up by other transducers and each transducer in turn emits its own signal. The presence of any void, honeycombing, anomaly inside the concrete changes the acoustic impedance of concrete at that location. As a result, the ultrasonic pulse gets reflected back and is recorded as an echo. The UPE machine gives 2D scans of concrete surface as output as shown in section 7.4. The UPE image is based on the ultrasonic shear-wave test method and an extended Synthetic Aperture Focusing Technique (SAFT). The UPE technique has limited applications to concrete structures due to the assumption that concrete is single layer homogenous and isotropic material. Ultrasonic testing is an effective method for detecting internal defects in concrete structures. However, interpreting ultrasonic testing data is a crucial task requiring extensive expertise as elaborated in Section 7.6. The UPE method can detect the location of defects but cannot interpret size and shape of defects as reported by (*Zatar et al., 2024*).

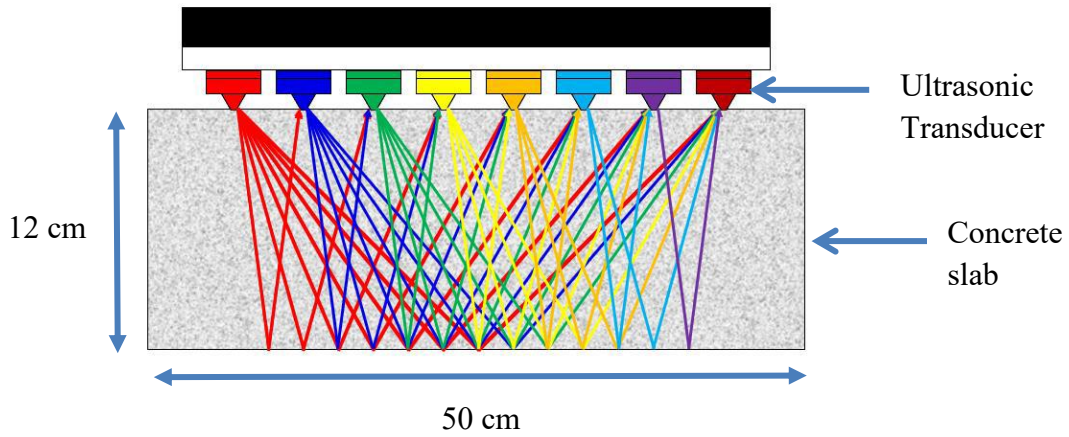


Figure 88 UPE experimental setup

7.4 UPE scan

The instrument can perform both A-scans as well as B-scans. An A-scan is the display of the ultrasound amplitude of a single measurement over time. B-scans are a pictorial representation of the A-scans of several measurements taken along a measuring line, as a section through the component perpendicular to the surface. The Figure 89 below shows multiple B-scans stitched together to create a line scan.

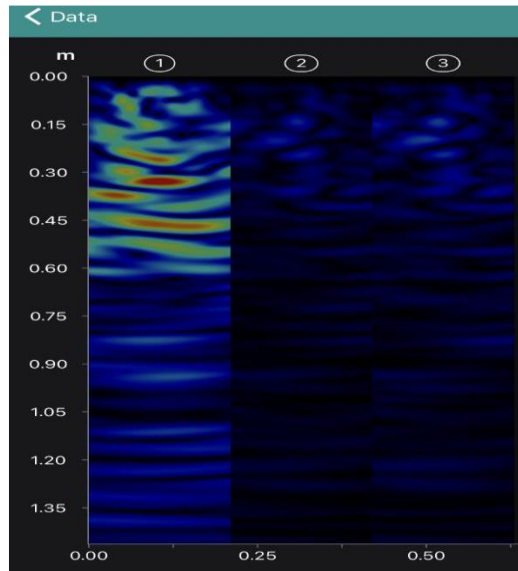


Figure 89 Line scan of slab using PD8050

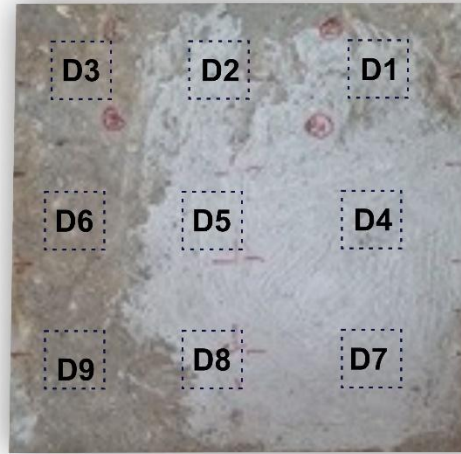
The B-scans provide a cross-sectional image of the test object perpendicular to the scanning surface in the plane through which the individual A-scans have been collected. Accurate estimation of defect depth requires precise calculation of pulse velocity. Pulse velocity is calculated by observing back wall echo on the B-scan and noting down time at which it occurs. The back wall echo is seen in Figure 89.

To perform UPE scan, it is first necessary to measure how much area the equipment can scan. Two B-scans were performed side by side and later combined using software supporting the PD 8050 to avoid overlapping. This is shown in Figure 90 below.



Figure 90 UPE B-scan of concrete slab

To interpret the results the defect locations were marked on the slab as shown in Figure 91 below. This step is of utmost importance as UPE scans need to be correlated with visual images.



Defect Locations

Figure 91 Defect locations on the surface of slab

A B-scan can be optimised in real time by adjusting gain and time gain compensation on transducers. The line scans can be made by stitching multiple B-scans together. The scanning is done from left to right. The B scan was performed in orientation as shown in Figure 91 above. The results of the above scans are shown in section 7.5.

7.5 Results

The Figure 92 below shows an line scan of the surface of the slab. The area scanned is demarcated with red box. The pattern of scanning is from left to right in horizontal direction. The B scans are also performed and multiple B scans were stitched together to get line scan. Figure 92 a below shows thermal image obtained using Infrared camera while Figure 92 c displays UPE line scan image.

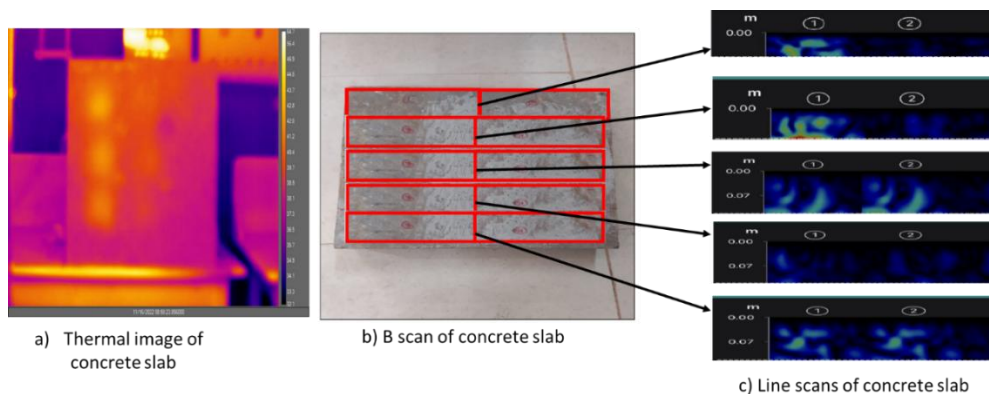


Figure 92 Comparison between thermal image and line scan of same concrete slab.

Enlarged images of Figures 92 b and 92 c are presented below for clarity. The Figure 93 below shows A-scan of the surface. The area scanned is demarcated with red box.

LOCATION	Scan-1 (SLAB-1)
GRID	1 x 2



Figure 93 A-scan of surface. Red box shows the extent of area scanned.

Figure 94 below shows line scan of the same red box as shown in Figure 93 above.

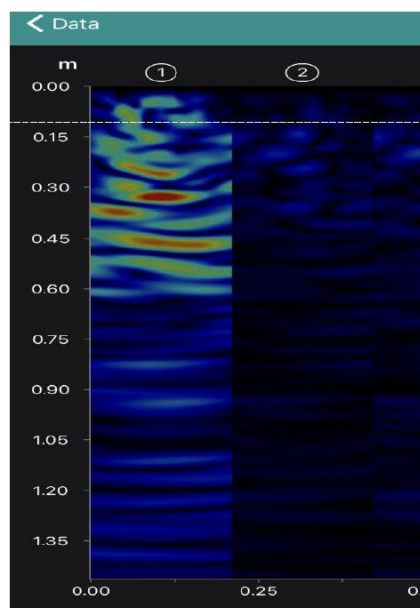


Figure 94 Line scan along red box 1

It is seen from Figure 94 above that there are multiple echos detected which indicate presence of some anomalies or reinforcement. The dotted line represents the bottom of slab which is of 12 cm thickness. There is only partial reflection which is evident from yellow colour in the line scan. This is in contradiction to red colour which is observed when there are air voids. Figure 95 below shows A-scan of area marked with red box. The scan indicates presence of anomalies on left hand side only.

LOCATION	Scan-2 (SLAB-1)
GRID	1 x 2



Figure 95 A-scan of surface. Red box shows the extent of area scanned.

Figure 96 below shows line scan of the area. The scan detects anomalies which are represented by yellow colour. Yellow colour indicates partial reflection of echo. At bottom of slab there is full reflection called back wall echo. This was used to calculate pulse velocity.

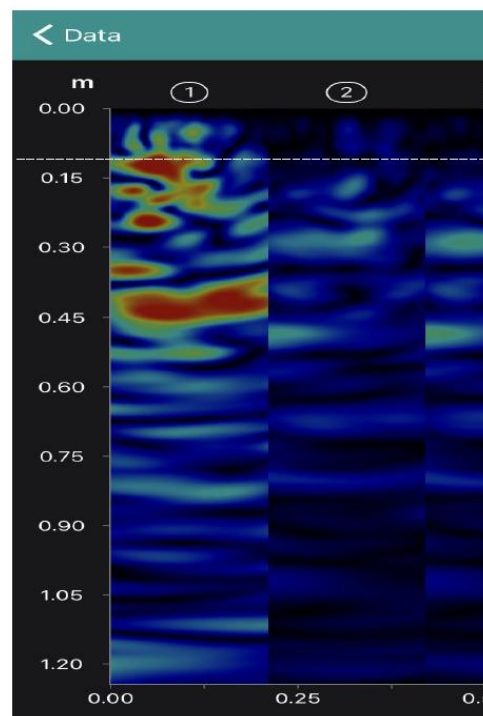


Figure 96 Line scan along red box 2

Figure 97 below shows A-scan of area marked with red box. The scan indicates presence of minor anomalies.

LOCATION	Scan-3 (SLAB-1)
GRID	1 x 2



Figure 97 A-scan of surface. Red box shows the extent of area scanned.

Figure 98 below shows line scan of the area marked in Figure above. The scan does not indicate the nature and extent of anomaly.

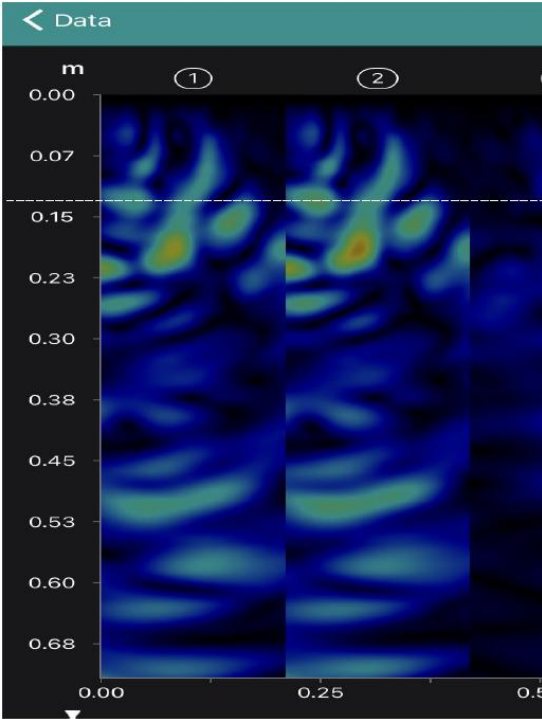


Figure 98 Line scan along red box 3

Figure 99 below shows A-scan of area marked as red box. The scan indicates presence of minor anomalies.

LOCATION	Scan-4 (SLAB-1)
GRID	1 x 2



Figure 99 A-scan of surface. Red box shows the extent of area scanned.

Figure 100 below shows line scan of the area marked in Figure above. The scan does not indicate the nature and extent of anomaly.

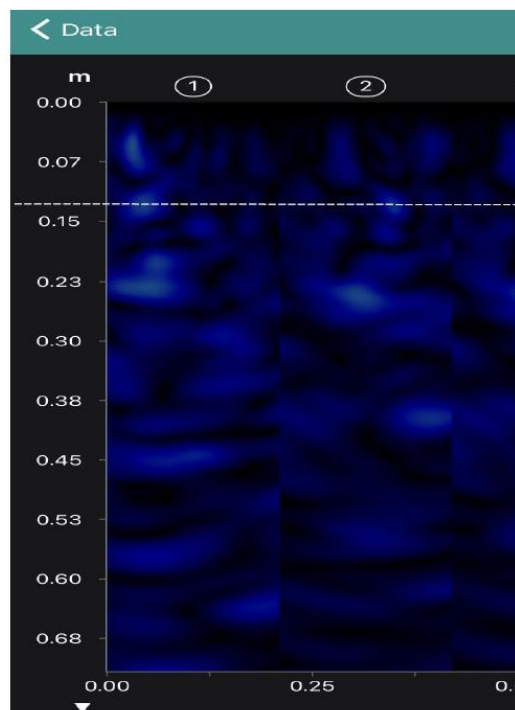


Figure 100 Line scan along red box 4

Figure 101 below shows A-scan of the bottom strip of slab marked by red box. The scan indicates presence of anomalies along the surface. To verify this line scan was taken along the strip.

LOCATION	Scan-4
GRID	1 x 2



Figure 101 A-scan of surface. Red box shows the extent of area scanned.

Figure 102 below shows line scan along the red box shown above. The scans show partial echos indicating presence of anomalies.

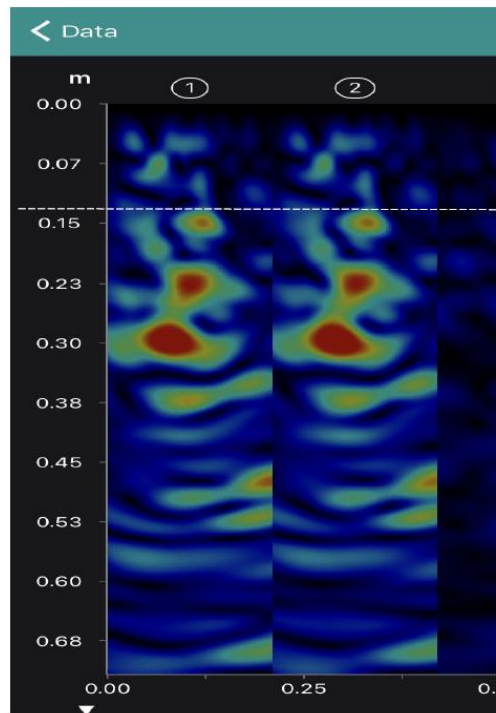


Figure 102 Line scan along red box 5

It is seen from all line scans above that there are multiple echos detected which indicate presence of some anomalies or reinforcement. There is only partial reflection which is evident from yellow colour in the line scan. Usually presence of air void or defect in slab is indicated by red colour echo in UPE scan. The full reflection observed at some depth below is called back wall echo which indicates variation in material and hence boundary of object. The above

scans when compared to thermal images validate that UPE lacks sufficient resolution to identify defects close to the surface which is also concluded by (Janku *et al.*, 2019).

7.6 Observations

The ultrasonic pulse echo measurements are carried out on laboratory cast concrete slab on which previously infrared thermography is carried out. The results of both the tests are compared based on ability to detect defect depth and extent of damage. The measurements performed showed that defects embedded inside the slab were visible in the thermal images while in UPE scans it was very difficult to identify. Infrared Thermography is very successful at locating defects if the width to depth ratio of the defect is more than 2. The Infrared Thermography technique is faster of both methods as it is a quick scan method. Infrared Thermography is capable of accurately determining the shape and size of defects. An advanced thermal camera is equipped with a laser rangefinder, which is helpful for determining the size of the delaminated area. The UPE technique somewhat falls behind in terms of being able to determine the exact shape and size of defects (Janku *et al.*, 2019). The accuracy of UPE depends on calibration for pulse velocity that is calculated based on back wall echo. It is however effective for deeper defect depth measurements. The cost of UPE equipment is similar to that of good quality infrared camera. A comparison of the UPE method and Infrared method with regards to parameters like power requirements, manpower and setup requirements is shown in Table 30.

Table 30 Comparison between Ultrasonic Pulse Echo (UPE) and Infrared Thermography (IRT) method (Janku *et al.*, 2019)

Criteria	Ultrasonic Pulse Echo (UPE)	Infrared Thermography (IRT)
Power source	Battery powered.	Battery powered or AC cord power, external heating source for active thermography.
Manpower	High trained operators who can do signal analysis also.	Low skill operators to gather data, higher skill for processing.
Speed of results interpretation	Slow as signal analysis and post processing is required	Fast interpretation. Latest cameras softwares have basic processing options.

	with correlation to visual images.	
Testing speed	Slow as proper coupling of transducer is required to surface and requires multiple scans along surface.	Non contact rapid scanning. Covers large area in single measurement.
Setup requirements	Includes cables and transducer. Can operate in any environment.	Compact cameras but high powered halogen lamps required for active thermography.

From the Table 30 it can be seen that UPE is suitable for localised inspection of concrete surface with longer inspection and result interpretation time. The Infrared Thermography method is best suited for wide surface rapid inspections with faster processing time using the methods developed in this study. The above observations show that active infrared thermography combined with techniques developed in this study to calculate extent and depth of defects can be an effective method for rapid inspection of concrete structures inspection.

Chapter 8

Results and Discussions

8.1 Introduction

The research objectives outlined in this thesis aim to develop Infrared Thermography as a suitable Non-Destructive Testing method for use in construction industry. The infrared thermography technique has found application in nuclear, food, paper, wood and plastic industries. However, its use in the construction industry is limited to detecting leakages in plumbing and heat losses in buildings (*Bagavathiappan et al., 2013*). The study conducted in this thesis focuses on developing methods to extract damaged area from thermal images. Also, techniques are developed to predict depth of sub-surface defects located inside concrete slab. The thermal image post processing techniques are applied on recorded thermal sequences obtained from the experiment to locate deeper defects. A comparison study was done between Infrared Thermography and Ultrasonic Pulse Echo (UPE) method. The study found that defects could be detected more efficiently using infrared thermography. This section presents the results and discussions of the research objectives outlined in this study.

8.2 Method to calculate defect area in concrete from thermal images

Section 3.4 summarizes all the results of defect area calculation from thermal images. Table 8 shows the comparison of actual defect area and defect area obtained using program. The results of the experimental study are summarized in Table 8. It is observed that as heating time increases, error between estimated area and actual defect area decreases. The experiment was simulated in FEA software to check if there are any inconsistencies in experimental results. Tables 10 and 11 compare experimental and simulation results. It is found that thermal images obtained from FEA simulation have lower error percentage compared to thermal images obtained from the experiment. The results of parametric study are shown from Figures 21 to 26. The magnitude of heat source and distance of heat source from surface of the slab are varied. Figures 21 to 23 show results for defect occupying 3% of slab surface area. Figures 24 to 26 show results for defect occupying 5% of slab surface area. It is observed from all graphs that minimum 30 minutes of thermal excitation of the slab surface is required to clearly identify defect location in thermal image when distance of source from slab surface is 0.85 m and 1.35 m. However when distance of source from slab is 0.60 m, minimum 45 minutes of thermal excitation is required for the defects to be visible. This is because of the concentration of radiation from the heat source at a small area of slab due to it being very close to the surface. It is observed from Figures 21 to 23 that the area calculated using program shows increasing

trend when the distance of the source from slab is 0.85 m and 1.35 m. However, it is observed that area calculated using program shows decreasing trend when the distance of the source from slab is 0.60 m. In Figures 24 to 26 it is observed that the error percentage increases when the distance of the heating source from the slab surface is increased. The plots shown in Figures 24 to 26 when distance of source is 0.60 m and 0.85 m shows decreasing trend till 90 minutes of thermal excitation. However, they show increasing trend when thermal excitation time is increased beyond 90 minutes. The plot for 1.35 m shows an increasing trend upto 180 minutes of thermal excitation.

In this study, FEA simulation of a concrete slab subjected to experimentation has been developed. The FEA simulation can successfully locate defects by showing higher temperature over defect area identified from thermal images. (Zhao *et al.*, 2013) used spatial processing techniques and MATLAB to find area of defects in retaining wall. It is found that obtained area is closer to actual area when amount of thermal excitation is increased. It is also found that if heating source is kept very close to concrete surface then non-uniform heating is produced and as a result there is delay in observation of defect area. The advantage of FEM models as shown in this study is, they help in reducing burden of expensive and time-consuming experimentation. They can help in identifying optimum thermal excitation time and distance to obtain accurate representation of sub-surface defects before going to field. They can also be used to estimate optimum thermal contrast between defect and sound area (Hiasa *et al.*, 2017).

8.3 FE simulation technique (Indirect method) to obtain defect depth

A pseudo experiment of Lock-in Infrared Thermography was conducted on a concrete slab modelled in FEA software. The Lock-in Infrared Thermography experiment is simulated by applying thermal excitation on the surface of the slab in the form of heat flux. It is observed from Figure 41 that the type of wave does not have an effect on defect depth detection. The percentage error between actual depth of defect and depth obtained from temperature contour is 2% which is fairly accurate. It is also observed that as thickness of defect increases the error between the actual depth and depth obtained from temperature contour increases. It is also observed that from the surface temperature graphs of slab surface, a peak appears at location of defects. The temperature contour in Figure 32 is plotted based on temperature data of the vertical section shows change in slope at some distance from surface. This is a critical observation to accurately calculate defect depth. The FEA simulation is successfully utilized to simulate thermography experiment. Cannas *et al.*, (2012) with aim to evaluate reliability of infrared thermography in building diagnosis developed an experimental program using a

concrete wall with different defects. This experiment was successfully replicated numerically using COMSOL Multiphysics software. *Showunmi, (2013)* used FEM model developed in ABAQUS to establish effectiveness of infrared thermography for Non-Destructive Testing of Steel Concrete composites. Thus it is a fairly accurate method for determining depth of defect. Thermographic study was performed on GFRP curved composite panels with sub-surface defects which were either artificially induced and from static loading by *Pastuszak, (2016)*. FEA model of the experiment was created to model transient heat transfer and results were compared to experimental results. The authors found that geometry of defects could be located precisely using FEA simulation.

8.4 Direct method to calculate defect depth based on thermal contrast

It is observed from Figure 56 and Equation 13 that the defect depth calculated will vary with observation time and thermal diffusivity of concrete. Hence observation time and thermal diffusivity are the two main parameters that will affect the defect depth calculation. The absolute thermal contrast graphs presented in this study are smoothened to fit 5th order polynomial curve. It is observed from Figure 46 to 48 and Figure 50 to 52 that the thermal contrast of a defect at same depth increased with an increase in the duration of heating. The parameters that affect thermal contrast are depth at which defect is located and duration of heating. From this study it is observed that there is no change in thermal contrast when thickness of defect is changed. The thermal contrast plots are utilised to obtain observation time. It is seen from Figure 49 and 53 that observation time varies non linearly with defect depth. The effect of heating time on the detection of defect depth is minimal. Thus change in the thickness of defect does not affect the detection of defect depth. However, the heating time has to be sufficient enough to set up required temperature gradient across the surface of slab in order to generate required thermal contrast.

The research data reported from (*Cotic et al., 2015*), (*Meola, 2007*), (*Maierhofer et al., 2006*), (*Hiasa et al., 2018*), (*Adeli & Sirca, 2018*) and (*Yehia et al., 2007*) shows that the authors adopted thermal contrast method to relate to depth of defect. The research reported in above literature is conducted in different parts of the world like Europe and South Korea. The above researches have motivated the authors to conduct such infrared thermography experiments in this part of the world. The equation to determine the depth of internal defect in concrete in this study incorporates the nonlinear thermal behaviour of concrete which is done only in this study. This study contributes to development of defect depth detection model based on the absolute thermal contrast to enhance its applicability to different regions of the world. Global production of cement is 4.2 billion tonnes per year as per Global Cement and Concrete

Association and is set to double to 9.8 billion tonnes per year by 2050. A significant portion of this is utilized for repair and rehabilitation of buildings in unplanned manner. The concrete repairs performed inconsistently will lead to frequent failure of repaired concrete, which is usually noticed. As per *Gurkan et al., (2018)* almost half of conventional concrete repairs fail in the field. The accurate detection of subsurface defects as outlined in this paper allows for timely maintenance and repair increasing the lifespan of concrete structures. This reduces the need for frequent reconstruction, thereby conserving resources and minimizing environmental impact. Reduction of reconstruction directly lower the carbon footprint associated with concrete production and construction activities. Th construction debris is also reduced as need for disposal of demolished buildings is reduced. The technique can also be adopted for quick damage assessment survey of buildings in areas affected by natural disasters. Hence the infrared thermography to be promoted and adopted for regular monitoring of concrete structures for precise revealing of internal cracks and damaged region which will aid in deciding early repairs. This will play a crucial role in promoting sustainable building practices and contribute to sustainability of maintaining built environment. Thermal images obtained from an infrared camera show that defects at a depth of 5 cm were not visible. The same has been verified from the thermograms obtained using FEA simulation, as shown in Figure 55 (a) and (b). For the detection of hidden subsurface defects at greater depths, there should be a sufficient temperature gradient between the subsurface defect inside the slab and the surface above the defect. As the subsurface defects in this experimental study at a depth of 5 cm had a narrower width proportional to the depth from the surface, no large temperature gradient formed on the surface when using a thermal camera. This was verified via thermography simulation via FEA. Hence, it is concluded that reliable results can be obtained for defects with depths less than 5 cm.

The defects upto 8 cm depth were considered in study by *Pozzer et al., (2024)*. The defects with a width-to-depth ratio greater than 2 are visible only in the raw thermal images which is verified from the current study. An empirical equation relating observation time and thermal diffusivity is developed taking into account non-linear thermal behaviour of concrete to predict the depth of defects. The non-linear thermal behaviour of concrete is used first time in developing relation to determine depth of damage in concrete. The depth of the defect predicted by the empirical Equation developed in this research (equation 8) is compared with the depth obtained from the equation developed by *Huh et al. (2018)* and is reported to have lower error. The similar study was conducted by *Pedram et al., (2022)* who developed an equation relating depth of defect with initial temperature of slab and observation time. However they did not use thermal diffusivity in their approach. The thermal diffusivity of

concrete is an important parameter which has been considered in this research. The equation proposed in this study can predict the depth of defects from thermograms with less error. The determination of depth of defect is important to help determine type of repair method to use. The proposed Equation No 13 can be easily used to find depth of sub-surface defects in structures monitored using thermal scanning. The input parameters required are only thermal diffusivity of concrete and observation time which is readily available while conducting active infrared thermography scanning.

8.5 Technique to identify deeper defects in concrete using post processing methods

The thermography experiments conducted in this research found that defects are visible in the raw thermal images if the Width to Depth ratio (WTDR) is more than or equal to 2. The Signal to Noise Ratio (SNR) is used to measure detectability of defects. It is observed that the Fourier Transform (Phase) method increases detectability of defects that are having width to depth ratio less than 2. This is observed from Figure 78 and 81. The plots in Figures 78 and 81 also show that Multiscale Retinex method improves detectability of defects that are having width to depth ratio more than 2. The Differentiated Absolute Contrast (DAC) method gives rise to higher image clarity after post processing. However it is observed that defect area gets reduced in post processed thermal image. The Principle Component Thermography (PCT) method enhances the detectability of defects which are having width to depth ratio more than 2 as seen in Figure 79,80,82 and 83. However the deeper defects are not seen clearly in post processed thermal images. The Wavelet Transform and Markov Error contrast reduce the clarity of defects in images. The Pulse Phase Thermography (PPT) method can identify deeper defects. The Pulse Phase Thermography (PPT) method involves conducting Fast Fourier Transform (FFT) on recorded thermal sequences *Maierhofer et al., (2006)*.

8.6 Comparison of Infrared Thermography with Ultrasonic Pulse Echo (UPE) (Experimental verification)

The concrete slab used for active infrared thermography experiment is scanned using Ultrasonic Pulse Echo (UPE) method. The defect detection capability of both methods is compared. The measurements performed showed that defects embedded inside the slab were visible in the thermal images obtained from infrared thermography. However, in UPE scans it is very difficult to identify defects due to partial echoes. Usually, defect is identified as a red colour spot in UPE scans. Infrared Thermography was very successful at locating defects provided the width to depth ratio is more than 2. The infrared thermography technique is faster of both methods as it is a quick scan method. The infrared thermography technique is capable of accurately determining the shape and size of defects as explained earlier. UPE somewhat

falls behind in terms of being able to determine the exact shape and size of defects as concluded by *Janku et al., 2019*. The accuracy of UPE depends on calibration with respect to pulse velocity that is calculated based on back wall echo. It is only effective for defects located at deeper depths. From the Table 30 it can be seen that UPE is suitable for localised inspection of concrete surface with longer inspection and result interpretation time. The Infrared Thermography method is best suited for wide surface rapid inspections with faster processing time using the methods developed in this study. The cost of UPE equipment is similar to that of good quality infrared camera. The findings in this study prove that active infrared thermography combined with techniques developed in this study to calculate extent and depth of defects can be an effective method for rapid inspection of concrete structures inspection.

Chapter 9

Conclusions and future scope

9.1 Conclusions

The specific conclusions drawn from this work are listed below:

- The thermal images with processing techniques serve as a tool for quantifying the extent of damage within the concrete. The research presented in this thesis indicates that the identification of defect area becomes more accurate as the duration of thermal excitation increases, although there is a time constraint necessary for achieving thermal equilibrium. Furthermore, it is concluded that the distance of the heating source is the primary factor influencing the accuracy of damage area identification in stepped thermography.
- The indirect method of plotting temperature contours from thermal images on vertical sections can determine the depth of defects with an accuracy of up to 2% error. It is concluded that the intensity and duration of thermal excitation do not influence the precision of depth detection in lock-in thermography.
- The equation formulated in this study for calculating defect depth from thermal images demonstrates a high level of accuracy over similar equation in literature. This equation has been evaluated on defects with a width-to-depth ratio of 2, extending to a depth of 10 cm, and has shown to identify defect depths with minimal error. It is concluded that as the depth of the defect increases, the observation time also increases, while the thickness of the defect does not influence the identification of its depth.
- The infrared thermography technique proves to be highly effective in identifying deeper defects, provided that the ratio of defect width to depth exceeds 2. This method offers a rapid scanning capability, making it quicker than the Ultrasonic Pulse Echo (UPE) method. Additionally, infrared thermography can precisely assess the shape and dimensions of defects.
- The observations presented above indicate that the integration of active infrared thermography with the methodologies developed in this study for assessing the extent and depth of defects is highly effective for the inspection and monitoring of concrete structures.

9.2 Future scope

Several possibilities exist for future work based on this study.

- The defect area identification studies can be extended further by investigating effect of thermal excitation beyond 60 minutes on the slab.
- The indirect method demonstrated in this chapter has yielded accurate defect depth detection. Further validation of this method is required considering field conditions.
- An obvious advance would be to use multiple post processing techniques on the recorded thermal sequences to reveal defects having width to depth ratio lesser than 2.
- The methods developed in this study can be integrated into infrared camera to develop a system where along with raw thermal images, results like extent of damage, depth of damage and type.
- A study can be taken up in future where predictive model can be developed based on statistical techniques to detect damage state on basis of surface temperature.
- Future studies can focus on predicting reinforcement corrosion.

Chapter 10

References

1. Milovanović, B., & Banjad Pečur, I. (2014). Detecting Defects in Reinforced Concrete using the Method of Infrared Thermography. *Croatian Society of Non-Destructive Testing (CrSNDT)*.
2. Oh, T., Kee, S., Arndt, R., Popovics, J., & Zhu, J. (2012). Comparison of NDT methods for assessment of a concrete bridge deck, *Journal of Engineering Mechanics*, 193(3), 305–314. [https://doi.org/10.1061/\(ASCE\)EM.1943-7889.0000441](https://doi.org/10.1061/(ASCE)EM.1943-7889.0000441).
3. Naik, M., Hegde, G., & Giri, L. (2022). Technique to determine depth of sub surface defects in concrete structures using infrared thermography a simulation study using FEM. *Proceedings of EURO-MED-SEC-4*, 9(1). [10.14455/ISEC.2022.9\(1\).STR-54](https://doi.org/10.14455/ISEC.2022.9(1).STR-54).
4. Maierhofer, C., Brink, A., Röhlig, M., & Wiggensauser, H. (2003). Detection of shallow voids in concrete structures with impulse thermography and radar. *NDT & E International*, 36, 257–263. [doi: 10.1016/S0963-8695\(02\)00063-4](https://doi.org/10.1016/S0963-8695(02)00063-4).
5. Hiasa, S., Birgul, R., & Catbas, F.N., (2017). A data processing methodology for infrared thermography images of concrete bridges. *International Journal of Computers and Structures*, 190, 205-218. [doi: http://dx.doi.org/10.1016/j.compstruc.2017.05.011](https://doi.org/10.1016/j.compstruc.2017.05.011).
6. Cotič, P., Kolarič, D., Bosiljkov, VB., Bosiljkov, V., & Jagličić, Z. (2015). Determination of the applicability and limits of void and delamination detection in concrete structures using infrared thermography. *NDT & E International*, 74, 87–93. [doi: 10.1016/j.ndteint.2015.05.003](https://doi.org/10.1016/j.ndteint.2015.05.003).
7. Meola, C. (2007). A new approach for estimation of defects detection with infrared thermography. *Materials Letters*, 61(3), 747-750. <https://doi.org/10.1016/j.matlet.2006.04.120>
8. Maierhofer, Ch., Arndt, R., Röhlig, M., Rieck, C., Walther, A., Scheel, H., & Hillemeier, B. (2006). Application of impulse-thermography for nondestructive assessment of concrete structures. *Cement & Concrete Composites*. 28, 393–401. <https://doi.org/10.1016/j.cemconcomp.2006.02.011>
9. Hiasa, S., Birgul, R., Matsumoto, M., & Necati Catbas, F. (2018). Experimental and Numerical Studies for Suitable Infrared Thermography Implementation on Concrete Bridge Decks. *Measurement*, 121, 144-159. [doi: https://doi.org/10.1016/j.measurement.2018.02.019](https://doi.org/10.1016/j.measurement.2018.02.019).

10. Adeli, H., & Sirca, G. (2018). Infrared Thermography for Detecting Defects in Concrete Structures. *Journal of Civil Engineering and Management*, 24(7), 508-515. <https://doi.org/10.3846/jcem.2018.6186>.
11. Yehia, S., Abudayyeh, O., Nabulsi, S., & Abdelqader, I., (2007). Detection of Common Defects in Concrete Bridge Decks using Non Destructive Evaluation Techniques, *Journal of Bridge Engineering*, 12, 215-225. [10.1061/\(ASCE\)1084-0702\(2007\)12:2\(215\)](https://doi.org/10.1061/(ASCE)1084-0702(2007)12:2(215)).
12. Cheng, CC., Cheng, TM. & Chiang, CH., (2008). Defect detection of concrete structures using both infrared thermography and elastic waves. *Automation in Construction*, 18,87–92. [doi: 10.1016/j.autcon.2008.05.004](https://doi.org/10.1016/j.autcon.2008.05.004).
13. Aggelis, D.G., Kordatos, E.Z., Soulioti, D.V., & Matikas, T.E., (2020). NDT approach for the characterization of subsurface cracks in concrete. *Construction and Building Materials*, 25, 3089–3097. <https://doi.org/10.1016/j.conbuildmat.2010.12.045>
14. Sirieix, C., Lataste, J. F., Breyse, D., Naar, S. & Derobert, X. (2007). Comparison of nondestructive testing: Infrared thermography, electrical resistivity and capacity methods for assessing a reinforced concrete structure. *Journal of Building Appraisal*, 3(1), 77–88, <https://doi.org/10.1057/palgrave.jba.2950065>.
15. Vaghefi, K., de Melo e Silfa, H., Harris, D., & Ahlborn, T. (2011). Application of thermal IR imagery for concrete bridge inspection. *Proceedings of the PCI National Bridge Conference, Salt Lake City, UT*.
16. Yehia, S., Abudayyeh, O., Nabulsi, S., & Abdelqader, I. (2007). Detection of Common Defects in Concrete Bridge Decks Using Non-destructive Evaluation Techniques. *Journal of Bridge Engineering*, 12, 215-225. [10.1061/\(ASCE\)1084-0702\(2007\)12:2\(215\)](https://doi.org/10.1061/(ASCE)1084-0702(2007)12:2(215)).
17. Scalbi, A., Olmi, R., Inglese, G. (2019). Evaluation of fractures in a slab by means of laser spot thermography. *International Journal of Heat and Mass Transfer*, 141, 282-293. <https://doi.org/10.1016/j.ijheatmasstransferj.2019.06.082>
18. Milovanović, B., & Pečur, I. (2016). Principle component thermography for defect detection in reinforced concrete structures. *Advances in Cement and Concrete Technology in Africa At: Dar es Salaam, Tanzania, Advances in Cement and Concrete Technology in Africa, Proceedings 2nd International Conference*.
19. Chatterjee, K., (2011). Development of Simulator and Image Processing Tools for Multi Technique Thermography. *Doctoral Thesis. Indian Institute of Technology, New Delhi*.
20. Shengli, Li., Shiji, S., Liu, Y., Wanshuai, Q., Jiang, N., Zheng, P., Cui, C., Han, S., Gao, X., Kai, Z. (2024). Infrared thermography detection of grouting defects in post-tensioned tendon ducts under active thermal excitation. *Measurement*, 234. <https://doi.org/10.1016/j.measurement.2024.114852>

21. Tuli, S., (2011). *Sub-surface Thermal Wave Imaging*. 1–13.
22. Maldague, X., & Galmiche, F. (2001). Advances in Pulsed Phase Tomography. *Infrared Physics & Technology*, 43, 175–181. [doi: 10.1016/S1350-4495\(02\)00138-X](https://doi.org/10.1016/S1350-4495(02)00138-X).
23. Gabriel, D., Ileana, R., Diana, C., & Stefan, L. (2015). Thermal Response for Reinforced Slab Analyzed with active Infrared Thermography and Comsol Multiphysics. *Applied Mechanics and Materials*, 760, 627-632. [doi:10.4028/www.scientific.net/AMM.760.627](https://doi.org/10.4028/www.scientific.net/AMM.760.627).
24. Huh, J., VH, Mac, QH, Tran, K Lee, J Lee, & C Kang. (2018). Detectability of Delamination in Concrete Structure Using Active Infrared Thermography in Terms of Signal-to-Noise Ratio. *Appl. Science*, 8. [doi:10.3390/app8101986](https://doi.org/10.3390/app8101986).
25. Pedram, M., Taylor, S., Hamill, G., Robinson, D., O'Brien, E.J., Uddin, N. (2022). Experimental evaluation of heat transition mechanism in concrete with subsurface defects using infrared thermography, *Construction and Building Materials*, 360. <https://doi.org/10.1016/j.conbuildmat.2022.129531>.
26. Hiasa, S., Birgul, R., Matsumoto, M., & Necati Catbas, F. (2018). Investigation of effective utilisation of infrared thermography (IRT) through advanced finite element modelling, *Construction and Building Materials*. 150, 295-309. doi: <https://doi.org/10.1016/j.conbuildmat.2017.05.175>.
27. Pozzer, S., Omid, Z., El Refai, A., Lopez, F., Ibarra-Castaneda, C., Maldague, X. (2024). Passive infrared thermography for subsurface delamination detection in concrete infrastructure: Capabilities, *Construction and Building Materials*, 419. <https://doi.org/10.1016/j.conbuildmat.2024.135542>
28. Gu, J.C., Unjoh, S., Naito, H. (2020). Detectability of delamination regions using infrared thermography in concrete members strengthened by CFRP jacketing. *Composite Structures*, 245. <https://doi.org/10.1016/j.compstruct.2020.112328>
29. Panella, F.W., Pirinu, A., & Dattoma, V. (2021). A Brief Review and Advances of Thermographic Image – Processing Methods for IRT Inspection: A Case of Study on GFRP Plate. *Experimental Techniques*, 45, 429-443. <https://doi.org/10.1007/s40799-020-00414-4>.
30. Pedram, M., Taylor, S., Hamill, G., Robinson, D., O'Brien, E.J., & Uddin, N. (2024). Objective characterisation of reinforced concrete with progressive corrosion defects through clustering and thresholding of infrared images, *Measurement*, 225. <https://doi.org/10.1016/j.measurement.2023.114017>
31. Yumnam, M., Gupta, H., Ghosh, D., & Jaganathan, J. (2021). Inspection of concrete structures externally reinforced with FRP composites using active thermography: A

review, *Construction and Building Materials*, 310.
<https://doi.org/10.1016/j.conbuildmat.2021.125265>.

32. Sultan, AA., & Washer, G. (2017). A pixel-by-pixel reliability analysis of infrared thermography (IRT) for the detection of subsurface delamination. *NDT & E International*, 92, 177–186. [doi: 10.1016/j.ndteint.2017.08.009](https://doi.org/10.1016/j.ndteint.2017.08.009).
33. Janků, M., Cikrle, P., Grosek, J., Anton, O., & Stryk, J. (2019). Comparison of infrared thermography, ground-penetrating radar and ultrasonic pulse echo for detecting delaminations in concrete bridges, *Construction and Building Materials*, 225, 1098-1111. <https://doi.org/10.1016/j.conbuildmat.2019.07.320>
34. Madruga, F., Ibarra-Castanedo, C., Olga, C., López-Higuera, J., & Maldague, X. (2010). Infrared thermography processing based on higher-order statistics. *NDT & E International*, 43, 661-666. <https://doi.org/10.1016/j.ndteint.2010.07.002>.
35. M. Rodríguez-Martín, S. Lagüela, D. González-Aguilera, & J. Martinez (2015). Prediction of depth model for cracks in steel using infrared thermography. *Infrared Physics & Technology*, 71, 492-500. <https://doi.org/10.1016/j.infrared.2015.06.013>.
36. Moskovchenko, A., Švantner, M., Vavilov, V., & Chulkov, A. (2022). Analyzing probability of detection as a function of defect size and depth in pulsed IR thermography. *NDT & E International*, 130. <https://doi.org/10.1016/j.ndteint.2022.102673>
37. Sakagami, T., & Kubo, S. (2002). Development of a new non-destructive testing technique for quantitative evaluations of delamination defects in concrete structures based on phase delay measurement using lock-in thermography, *Infrared Physics & Technology* 43, 311–316. [https://doi.org/10.1016/S1350-4495\(02\)00157-3](https://doi.org/10.1016/S1350-4495(02)00157-3)
38. Omar, T., M.L., Nehdi, & T., Zayed (2018). Infrared thermography model for automated detection of delamination in RC bridge decks. *International Journal of Construction and Building Materials*, 168, 313-327. [doi:10.1016/j.conbuildmat.2018.02.12](https://doi.org/10.1016/j.conbuildmat.2018.02.12).
39. Ishikawa, M., Hatta, H., Habuka, Y., Fukui, R., & Utsunomiya, S. (2013). Detecting deeper defects using pulse phase thermography. *Infrared Physics and Technology*, 57, 42-49. <http://dx.doi.org/10.1016/j.infrared.2012.11.009>.
40. Tran, Q.H., Huh, J., Mac Van, H., Kang, C., & Donyeob, H. (2018). Effect of rebars on detectability of subsurface defects in concrete bridges using square pulse thermography. *NDT & E International*, 100, 92-100. <http://doi.org/10.1016/j.ndteint.2018.09.001>.
41. Tashan, J., & Al-Mahaidi, R.(2014). Detection of Cracks in Concrete Strengthened with CFRP systems Using Infra-Red Thermography, *Composites Part B: Engineering*, 64, 116-125. [doi: http://dx.doi.org/10.1016/j.compositesb.2014.04.011](http://dx.doi.org/10.1016/j.compositesb.2014.04.011)

42. Zhao, G., & Chen, J.G. (2013). Infrared thermographic inspection for concrete retaining wall. *Electron J Geotech Engg*, 18, 1521-1528.
43. Meola, C., & Carlomagno, G. (2004). Recent Advances in the use of Infrared Thermography. *Measurement Science and Technology*, 15, R27-R58. [doi: 10.1088/0957-0233/15/9/R01](https://doi.org/10.1088/0957-0233/15/9/R01).
44. Kook-Han, K., Sang-Eun, J., Jin-Keun, K., & Sungchul, Y. (2003). An experimental study on thermal conductivity of concrete, *Cement and Concrete Research*, 33,363–371. [https://doi.org/10.1016/S0008-8846\(02\)00965-1](https://doi.org/10.1016/S0008-8846(02)00965-1)
45. Cannas, B., Carcangiu, S., Concu, G., & Trulli, N. (2012). Modeling of Active Infrared Thermography for Defect Detection in Concrete Structures. *Excerpt from Proceedings of the 2012 Conference in Milan*.
46. Lee, Y., Choi, M-S., Yi, S-T., & Kim, J-K. (2009). Experimental study on the convective heat transfer coefficient of early-age concrete. *Cement and Concrete Composites*, 31,60-71. [doi:10.1016/j.cemconcomp.2008.09.009](https://doi.org/10.1016/j.cemconcomp.2008.09.009)
47. Naik, M., Gaonkar, V., Hegde, G., & Giri, L.I. (2021). Detection of Defects in Concrete Structures by Using Infrared Thermography. In: Shukla, S.K., Chandrasekaran, S., Das, B.B., Kolathayar, S. (eds) *Smart Technologies for Sustainable Development. Lecture Notes in Civil Engineering*, 78. Springer, Singapore. https://doi.org/10.1007/978-981-15-5001-0_19
48. Naik, M., Hegde, G., & Giri, L.I. (2021). Optimization of Infrared Thermography for Damage Detection in Concrete Structures Using Finite Element Modelling. In: Das, B.B., Nanukuttan, S.V., Patnaik, A.K., Panandikar, N.S. (eds) *Recent Trends in Civil Engineering. Lecture Notes in Civil Engineering*, 105, Springer, Singapore. https://doi.org/10.1007/978-981-15-8293-6_15
49. Naik, M., Hegde, G., & Giri, L.I. (2020). Parameter Identification to Detect Damage in Reinforced Concrete Structures using Infrared Thermography, *National Conference on Civil Engineering “New and Effective Innovations, Technologies and Key Challenges 2020” (NCCE-NITK 2020)*, National Institute of Technology, Surathkal, Karnataka, India, January 30-31 2020.
50. Carroll, D., Lo, H., & Stiel, L. (1968). Thermal conductivity of gaseous air at moderate and high pressures. *Journal of Chemical & Engineering Data*, 13(1). <https://doi.org/10.1021/je60036a017>
51. B.N., Raja, Miramini, S., Duffield, C., Sofi, M., Mendis, P., & Zhang, L. (2019). The influence of ambient environmental conditions in detecting bridge concrete deck

- delamination using infrared thermography (IRT). *Structural Control Health Monitoring*. <https://doi.org/10.1002/stc.2506>
52. Gurkan, Y., Mustafa, S., & Ozgur, A. (2018). Engineered cementitious composites-based concrete. *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures*, 387-427. <https://doi.org/10.1016/B978-0-08-102181-1.00015-0>.
 53. Naik, M., Hegde, G., & Giri, L.I. (2024). A novel method based on thermal imaging and FEA simulation for depth prediction of internal defects in concrete slabs. *Journal of Building Engineering*, 95. <https://doi.org/10.1016/j.jobbe.2024.110228>
 54. D. J., Jobson, Z., Rahman, & G. A., Woodell (1997). A multiscale retinex for bridging the gap between color images and the human observation of scenes, *IEEE Transactions on Image Processing*, 6(7), 965-976. [doi: 10.1109/83.597272](https://doi.org/10.1109/83.597272)
 55. Z., Rahman, D. J., Jobson, & G. A., Woodell (1996). Multi-scale retinex for color image enhancement, *Proceedings of 3rd IEEE International Conference on Image Processing, Lausanne, Switzerland*, 3, 1003-1006. [doi: 10.1109/ICIP.1996.560995](https://doi.org/10.1109/ICIP.1996.560995).
 56. Gonzalez-Diaz, L., & Villalba, V. (2005). Resonances in the one-dimensional Dirac equation in the presence of a point interaction and a constant electric field. *Physics Letters A*, 352, 202-25. <https://doi.org/10.1016/j.physleta.2005.12.003>
 57. Klein, Matthieu, Xavier, P. V. Maldague, Mariacristina Pilla, & Antonio Salerno (2002). New absolute contrast for pulsed thermography. *Quantitative InfraRed Thermography*, 53-58. [10.21611/qirt.2002.004](https://doi.org/10.21611/qirt.2002.004)
 58. Larson, C., (2011). Document Flash Thermography. *MS Thesis. Utah State University*.
 59. Ibarra-Castanedo, C., & Maldague, X. P. V. (2005). Interactive Methodology for Optimized Defect Characterization by Quantitative Pulsed Phase Thermography. *Research in Nondestructive Evaluation*, 16(4), 175–193. <https://doi.org/10.1080/09349840500351846>
 60. Marinetti, Sergio & Grinzato, E. & Bison, Paolo & Bozzi, E. & Chimenti, M. & Pieri, Gabriele & Salvetti, Ovidio. (2004). Statistical analysis of IR thermographic sequences by PCA. *Infrared Physics & Technology*, 46, 85-91. [10.1016/j.infrared.2004.03.012](https://doi.org/10.1016/j.infrared.2004.03.012).
 61. Park, Gyu-Hee & Cho, Hwa-Hyun & Choi, & Myung-Ryul. (2008). A Contrast Enhancement Method using Dynamic Range Separate Histogram Equalization. *Consumer Electronics, IEEE Transactions on*. 54, 1981 - 1987. [10.1109/TCE.2008.4711262](https://doi.org/10.1109/TCE.2008.4711262).
 62. Rose, W. *Automated statistical analysis of Signal to Noise ratio*.
 63. Janků, M., Cikrle, P., Grosek, J., Anton, O., & Stryk, J. (2019). Comparison of infrared thermography, ground-penetrating radar and ultrasonic pulse echo for detecting

- delaminations in concrete bridges. *Construction and Building Materials*, 225, 1098-1111. <https://doi.org/10.1016/j.conbuildmat.2019.07.320>
64. Showunmi, T. (2013). Finite Element Infrared Thermography Study on Concrete and Steel-Concrete Composite Structures. *Master's Thesis. Department of Civil and Environmental Engineering. Lehigh University, Pennsylvania.*
 64. P.D., Pastuszak, (2016). Characterization of defects in curved composite structures using Active Infrared Thermography. *Procedia Engineering*, 157, 325-332. <https://doi.org/10.1016/j.proeng.2016.08.373>
 66. Zatar, W., Chen, G., Nghiem, H., & Xiao, F (2024). Ultrasonic Pulse-Echo Signals for Quantitative Assessment of Reinforced Concrete Anomalies. *Applied Sciences*, 14. <https://doi.org/10.3390/app14114860>
 67. Bagavathiappan, S., Lahiri, BB, Saravanan, T., Philip, J., & Jayakumar, T. (2013). Infrared thermography for condition monitoring-A review, *Infrared Physics & Technology*, 60, 35-55. <https://doi.org/10.1016/j.infrared.2013.03.006>

Publications

Conference Papers:

1. Naik, M., Gaonkar, V., Hegde, G., & Giri, L.I. (2021). Detection of Defects in Concrete Structures by Using Infrared Thermography. In: *Shukla, S.K., Chandrasekaran, S., Das, B.B., Kolathayar, S. (eds) Smart Technologies for Sustainable Development. Lecture Notes in Civil Engineering, vol 78. Springer, Singapore.* https://doi.org/10.1007/978-981-15-5001-0_19
2. Naik, M., Hegde, G., & Giri, L.I. (2021). *Optimization of Infrared Thermography for Damage Detection in Concrete Structures Using Finite Element Modelling.* In: *Das, B.B., Nanukuttan, S.V., Patnaik, A.K., Panandikar, N.S. (eds) Recent Trends in Civil Engineering. Lecture Notes in Civil Engineering, vol 105. Springer, Singapore.* https://doi.org/10.1007/978-981-15-8293-6_15
3. Naik, M., Hegde, G., & Giri, L.I. (2020). Parameter Identification to Detect Damage in Reinforced Concrete Structures using Infrared Thermography. *National Conference on Civil Engineering "New and Effective Innovations, Technologies and Key Challenges 2020" (NCCE-NITK 2020), National Institute of Technology, Surathkal, Karnataka, India.*
4. Naik, M., Hegde, G., & Giri, L.I. (2022). Technique to determine depth of Sub Surface defects in concrete structures using Infrared Thermography: A simulation study using

FEM. *Proceedings of International Structural Engineering and Construction*, 9(1), 2022
State-of-the-art Materials and Techniques in Structural Engineering and Construction
Edited by Holschemacher, K., Quapp, U., Singh, A., and Yazdani, S. Copyright © 2022
ISEC Press ISSN: 2644-108X. [www.doi.org/10.14455/ISEC.2022.9\(1\).STR-54](http://www.doi.org/10.14455/ISEC.2022.9(1).STR-54)

Journal Papers:

1. Naik, M., Hegde, G., & Giri, L.I. (2024). A novel method based on thermal imaging and FEA simulation for depth prediction of internal defects in concrete slabs. *Journal of Building Engineering*, 95. <https://doi.org/10.1016/j.jobbe.2024.110228>

Annexure A

Program to calculate area of damage

```
function spatial_calibration_demo()
% This demo allows you to spatially calibrate your image and then make distance or area
measurements.

global originalImage;
% Check that user has the Image Processing Toolbox installed.
clc; % Clear the command window.
close all; % Close all figures (except those of imtool.)
workspace; % Make sure the workspace panel is showing.
format long g;
format compact;
fontSize = 20;

hasIPT = license('test', 'image_toolbox');
if ~hasIPT
    % User does not have the toolbox installed.
    message = sprintf('Sorry, but you do not seem to have the Image Processing
Toolbox.\nDo you want to try to continue anyway?');
    reply = questdlg(message, 'Toolbox missing', 'Yes', 'No', 'Yes');
    if strcmpi(reply, 'No')
        % User said No, so exit.
        return;
    end
end

% Read in a standard MATLAB gray scale demo image.
folder = fullfile(matlabroot, '\toolbox\images\imdemos');
button = menu('Use which demo image?', 'CameraMan', 'Moon', 'Eight', 'Coins', 'Peppers', 'My
own...', 'Exit');
switch button
    case 1
        baseFileName = 'cameraman.tif';
```

```

case 2
    baseFileName = 'moon.tif';
case 3
    baseFileName = 'eight.tif';
case 4
    baseFileName = 'coins.png';
case 5
    baseFileName = 'peppers.png';
case 6
    % Get the name of the file that the user wants to use.
    defaultFileName = fullfile(cd, '*.*');
    [baseFileName, folder] = uigetfile(defaultFileName, 'Select an image file');
    if baseFileName == 0
        % User clicked the Cancel button.
        return;
    end
case 7
    return;
end

% Get the full filename, with path prepended.
fullFileName = fullfile(folder, baseFileName);
% Check if file exists.
if ~exist(fullFileName, 'file')
    % File doesn't exist -- didn't find it there. Check the search path for it.
    fullFileName = baseFileName; % No path this time.
    if ~exist(fullFileName, 'file')
        % Still didn't find it. Alert user.
        errorMessage = sprintf('Error: %s does not exist in the search path folders.',
fullFileName);
        uiwait(warndlg(errorMessage));
        return;
    end
end

% Read in the chosen standard MATLAB demo image.

```

```

originalImage = imread(fullFileName);
% Get the dimensions of the image.
% numberOfColorBands should be = 1.
[rows, columns, numberOfColorBands] = size(originalImage);
% Display the original gray scale image.
figureHandle = figure;
subplot(1,2, 1);
imshow(originalImage, []);
axis on;
title('Original Grayscale Image', 'FontSize', fontSize);
% Enlarge figure to full screen.
set(gcf, 'units','normalized','outerposition',[0 0 1 1]);
% Give a name to the title bar.
set(gcf,'name','Demo by ImageAnalyst','numbertitle','off')

message = sprintf('First you will be doing spatial calibration. ');
reply = questdlg(message, 'Calibrate spatially', 'OK', 'Cancel', 'OK');
if strcmpi(reply, 'Cancel')
    % User said Cancel, so exit.
    return;
end
button = 1; % Allow it to enter loop.

while button ~= 4
    if button > 1
        % Let them choose the task, once they have calibrated.
        button = menu('Select a task', 'Calibrate', 'Measure Distance', 'Measure Area',
'Exit Demo');
    end
    switch button
        case 1
            success = Calibrate();
            % Keep trying if they didn't click properly.
            while ~success
                success = Calibrate();
            end
        end
    end
end

```



```

if length(xi) < 2
    return;
end
% Plot the line.
hold on;
lastDrawnHandle = plot(xi, yi, 'y-', 'LineWidth', 2);

% Ask the user for the real-world distance.
userPrompt = {'Enter real world units (e.g. microns):','Enter distance in those units:'};
dialogTitle = 'Specify calibration information';
numberOfLines = 1;
def = {'microns', '500'};
answer = inputdlg(userPrompt, dialogTitle, numberOfLines, def);
if isempty(answer)
    return;
end
calibration.units = answer{1};
calibration.distanceInPixels = distanceInPixels;
calibration.distanceInUnits = str2double(answer{2});
calibration.distancePerPixel = calibration.distanceInUnits / distanceInPixels;
success = true;

message = sprintf('The distance you drew is %.2f pixels = %f %s.\nThe number of %s
per pixel is %f.\nThe number of pixels per %s is %f',...
    distanceInPixels, calibration.distanceInUnits, calibration.units, ...
    calibration.units, calibration.distancePerPixel, ...
    calibration.units, 1/calibration.distancePerPixel);
uiwait(msgbox(message));
catch ME
    errorMessage = sprintf('Error in function Calibrate().\nDid you first left click and then
right click?\n\nError Message:\n%s', ME.message);
    fprintf(1, '%s\n', errorMessage);
    WarnUser(errorMessage);
end

```

```

return; % from Calibrate()
end

%=====

=====

% --- Executes on button press in DrawLine.
function success = DrawLine()
try
    global lastDrawnHandle;
    global calibration;
    fontSize = 14;

    instructions = sprintf('Draw a line.\nFirst, left-click to anchor first endpoint of
line.\nRight-click or double-left-click to anchor second endpoint of line.\n\nAfter that I will
ask for the real-world distance of the line.');
```

title(instructions);

msgboxw(instructions);

subplot(1,2, 1); % Switch to image axes.

[cx,cy, rgbValues, xi,yi] = improfile(1000);

% Get the profile again but spaced at the number of pixels instead of 1000 samples.

hImage = findobj(gca,'Type','image');

theImage = get(hImage, 'CData');

lineLength = round(sqrt((xi(1)-xi(2))^2 + (yi(1)-yi(2))^2))

[cx,cy, rgbValues] = improfile(theImage, xi, yi, lineLength);

% rgbValues is 1000x1x3. Call Squeeze to get rid of the singleton dimension and
make it 1000x3.

rgbValues = squeeze(rgbValues);

distanceInPixels = sqrt((xi(2)-xi(1)).^2 + (yi(2)-yi(1)).^2);

distanceInRealUnits = distanceInPixels * calibration.distancePerPixel;

if length(xi) < 2

 return;

end

% Plot the line.

```

hold on;
lastDrawnHandle = plot(xi, yi, 'y-', 'LineWidth', 2);

% Plot profiles along the line of the red, green, and blue components.
subplot(1,2,2);
[rows, columns] = size(rgbValues);
if columns == 3
    % It's an RGB image.
    plot(rgbValues(:, 1), 'r-', 'LineWidth', 2);
    hold on;
    plot(rgbValues(:, 2), 'g-', 'LineWidth', 2);
    plot(rgbValues(:, 3), 'b-', 'LineWidth', 2);
    title('Red, Green, and Blue Profiles along the line you just drew.', 'FontSize',
14);
else
    % It's a gray scale image.
    plot(rgbValues, 'k-', 'LineWidth', 2);
end
xlabel('X', 'FontSize', fontSize);
ylabel('Gray Level', 'FontSize', fontSize);
title('Intensity Profile', 'FontSize', fontSize);
grid on;

% Inform user via a dialog box.
txtInfo = sprintf('Distance = %.1f %s, which = %.1f pixels.', ...
    distanceInRealUnits, calibration.units, distanceInPixels);
msgboxw(txtInfo);
% Print the values out to the command window.
fprintf(1, '%\n', txtInfo);

catch ME
    errorMessage = sprintf('Error in function DrawLine().\n\nError Message:\n%s',
ME.message);
    fprintf(1, '%s\n', errorMessage);
    WarnUser(errorMessage);

```

```

end
end % of DrawLine()

%=====
=====

function DrawArea()
global originalImage;
global lastDrawnHandle;
global calibration;
try
    txtInfo = sprintf('Left click to anchor vertices.\nDouble left click to anchor final point
of polygon. ');
    title(txtInfo);
    msgboxw(txtInfo);

    % Get size information.
    [rows, columns, numberOfColorBands] = size(originalImage);

    % Get a gray scale version.
    if numberOfColorBands > 1
        grayImage = rgb2gray(originalImage);
    else
        grayImage = originalImage;
    end

    subplot(1,2, 1); % Switch to image axes.
    % Ask user to draw a polygon.
    [maskImage, xi, yi] = roipolyold();

    % Draw the polygon over the image on the main screen.
    hold on;
    lastDrawnHandle = plot(xi, yi, 'r-', 'LineWidth', 2);
    numberOfPixels = sum(maskImage(:));
    area = numberOfPixels * calibration.distancePerPixel^2;

```

```

% Get the mean gray level of the gray scale image.
mean_GL = mean(grayImage(maskImage)); % Of the gray scale version.

% Print the area values out to the command window.
txtInfo = sprintf('Area = %8.1f square %s.\nMean gray level = %.2f', ...
    area, calibration.units, mean_GL);
fprintf(1, '%s\n', txtInfo);
title(txtInfo, 'FontSize', 14);

% Done with measurement of area.
% Now, just for fun, get the mean value and display the histogram.
if numberOfColorBands >= 3
    % It's a color image. Get the mean RGB Values.
    redPlane = double(originalImage(:, :, 1));
    greenPlane = double(originalImage(:, :, 2));
    bluePlane = double(originalImage(:, :, 3));
    mean_RGB_GL(1) = mean(redPlane(maskImage));
    mean_RGB_GL(2) = mean(greenPlane(maskImage));
    mean_RGB_GL(3) = mean(bluePlane(maskImage));
    fprintf('%s\nRed mean = %.2f\nGreen mean = %.2f\nBlue mean = %.2f', ...
        txtInfo, mean_RGB_GL(1), mean_RGB_GL(2), mean_RGB_GL(3));
end

% Just for fun, let's get its histogram within the masked region.
[pixelCount, grayLevels] = imhist(grayImage(maskImage));
subplot(1,2, 2); % Switch to plot axes.
cla;
bar(grayLevels, pixelCount);
grid on;
caption = sprintf('Histogram within area. Mean gray level = %.2f', mean_GL);
title(caption, 'FontSize', 14);
xlim([0 grayLevels(end)]); % Scale x axis manually.
% Show the mean as a vertical red bar on the histogram.
hold on;
maxYValue = ylim;

```

```

        line([mean_GL, mean_GL], [0 maxYValue(2)], 'Color', 'r', 'linewidth', 2);
catch ME
    errorMessage = sprintf('Error in function DrawArea().\n\nError Message:\n%s',
ME.message);
    fprintf(1, '%s\n', errorMessage);
    WarnUser(errorMessage);
end

end % of DrawArea()

%=====
=====

function msgboxw(message)
    uiwait(msgbox(message));
end

%=====
=====

function WarnUser(message)
    uiwait(msgbox(message));
end

=====

```

Annexure B

Program to calculate Signal to Noise Ratio (SNR)

```
X = imread('10 min.jpg');
L = 80; %length of snr box
w = 80; %width of snr box
%Submatrix Window
ymin = 80; %Starting row
ymax = 183; %Ending row
xmin = 205; %Starting Column
xmax = 308; %Ending Column
W = X(ymin:ymax,xmin:xmax);
m = ymax-ymin+1; %Number of Pixels in vertical direction
n = xmax-xmin+1; %Number of Pixels in horizontal direction
snr = zeros(m-L+1,n-w+1);
%Initialize SNR Storage Matrix
%SNR Horizontal Orientation 20x55
for i = 1:m-L+1

    for j = 1:n-w+1
        Y = W(i:L-1+i, j:w-1+j);
        %Border Inclusive
        mean = mean2(Y);
        std = std2(Y);
        snr(i,j) = mean/std;

    end

end

end
[a,b] = size(snr);
if a == 1

    %Maximum SNR Location; Top Left Corner of Box
    [snrmax, locmax] = max(snr);
    %Minimum SNR Location; Top Left Corner of Box
```

```

[snrmin, locmin] = min(snr);
y_max = ymin;
x_max = locmax+xmin;
y_min = ymin;
x_min = locmin+xmin;

figure(2)
hist(snr(:))
elseif b==1

%Maximum SNR Location; Top Left Corner of Box
[snrmax, locmax] = max(snr);
%Minimum SNR Location; Top Left Corner of Box
[snrmin, locmin] = min(snr);

y_max = locmax+ymin;
x_max = xmin;
y_min = locmin+ymin;
x_min = xmin;

else

figure(1) %Surface Plot
surf(snr)
figure(2) %Histogram
hist(snr(:))
[snrmax,Idx] = max(snr(:));
[snrmin,Idx_2] = min(snr(:));
%Maximum SNR Location; Top Left Corner of Box
[snrRowmax,snrColmax] = ind2sub(size(snr), Idx);
y_max = snrRowmax+ymin;
x_max = snrColmax+xmin;
%Minimum SNR Location; Top Left Corner of Box
[snrRowmin,snrColmin] = ind2sub(size(snr), Idx_2);
y_min = snrRowmin+ymin;

```

```

x_min = snrColmin+xmin;
figure (3) %Original Image
imshow(X);
figure (4) %Z contains the submatrix and the SNR box
Z = X;
Z(ymin:ymax,xmin:xmin) = 0;
Z(ymin:ymax,xmax:xmax) = 0;
Z(ymin:ymin,xmin:xmax) = 0;
Z(ymax:ymax,xmin:xmax) = 0;
Z(y_max,x_max:x_max+w-1) = 0;
Z(y_max+L-1,x_max:x_max+w-1) = 0;
Z(y_max:y_max+L-1,x_max) = 0;
Z(y_max:y_max+L-1,x_max+w-1) = 0;
imshow(Z);
end

```