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Date:
2020-04-01

Citation:
Raja, B. N. K., Miramini, S., Duffield, C., Sofi, M., Mendis, P. & Zhang, L. (2020). The influence of ambient environmental conditions in detecting bridge concrete deck delamination using infrared thermography (IRT). Structural Control and Health Monitoring, 27 (4), https://doi.org/10.1002/stc.2506.

Persistent Link:
https://hdl.handle.net/11343/245474

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The influence of ambient environmental conditions in detecting bridge concrete deck delamination using infrared thermography (IRT)

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ABSTRACT

Delamination is a serious form of deterioration in concrete bridge decks. Infrared thermography (IRT) is an advance non-destructive testing method for concrete bridge deck delamination detection by capturing the absolute thermal contrast (ΔT) on the concrete surface caused by the disruption in heat flow due to subsurface defects. However, as the ambient environmental conditions (e.g. wind velocity and solar radiation) of a bridge could significantly affect the measurement outcomes of IRT, the optimal times for infrared data collection are still unclear. In this paper, a series of experimental and numerical studies were carried out to investigate the effects of the rate of heat flux and wind velocity on ΔT on the surface of bridge decks with the aim of identifying the optimal inspection times for different geometry characteristics of delamination (i.e. size and depth). The developed model is firstly validated by the experimental data and then a series of parametric studies were carried out. The result shows that the heat flux rate plays an important role in the development of ΔT on concrete surface, especially for a relatively shallow and small size delamination. However, the influence of heat flux rate gradually diminishes with the increase in size and depth of delamination. In addition, it demonstrates that there is a positive linear correlation between the total heat energy (external irradiation) and square of the delamination depth. The current research represents an important step towards the development of an effective and efficient way for defect detection using IRT.

KEY WORDS

Bridge concrete decks; delamination; Infrared thermography (IRT); Non-destructive testing (NDT); absolute thermal contrast; heat flux

1. INTRODUCTION

Concrete bridge decks are most vulnerable components within the transportation infrastructure because they are subjected to continuous deterioration due to direct impact of repetitive heavy traffic loadings, thermal loadings, freeze and thaw cycles and various other

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/stc.2506

ambient environmental conditions [1-4]. The major problem encountered by the reinforced concrete bridge decks is sub-surface delamination caused by the corrosion of steel reinforcing bars (rebar), which is more evident in the structures where de-icing chemicals are used on the surface [5]. The delamination can lead to local expansion of steel, imposing local stresses on concrete and ultimately triggering cracks along the rebars in concrete [6, 7]. The delamination is normally not visible unless it breaks the surface and whole chunk of concrete spalls off, which further exposes the steel to environmental effects and thus accelerating the deterioration process [8]. This phenomenon has also been observed in the bridge girders and soffit, which sometimes threaten the safety in case of overpass highways. Therefore, it is necessary to detect the delamination in early stages so that the maintenance and preservation techniques could be applied beforehand to avoid uncontrolled spalling and damage of the bridges [9].

The bridges are traditionally monitored for subsurface delamination using chain drag and hammer sounding tests carried out by trained inspectors and qualified engineers [10]. These tests are based on the principle that the sound from dragging the chain or hitting the hammer on the deck changes from ringing (associated with sound deck) to the somewhat dull and hollow (associated with delamination) [11]. Although these techniques are low cost, simple and easy to apply, they are time-consuming, and the accuracy of results is highly sensitive to the surrounding noises and require experience of inspectors. Further, the traditional delamination techniques may require closure of traffic, even expose workers to dangerous working conditions.

Infrared thermography (IRT) is one of the advanced methods for non-destructive evaluation of the reinforced concrete bridges. IRT is an efficient and effective way for the rapid and safe evaluation of bridge components, including substructures, soffit areas and superstructures [9]. Although IRT has the capability of producing good results for the subsurface damage characterization, it has some drawbacks, such as lack of detail information about the depth of the defect [11], and low accuracy of measurements due to surface textures and environmental conditions [12].

IRT uses the temperature gradient between the defected and sound surface $(\Delta T = T_d - T_s)$ to identify the defect regions in concrete deck. All objects emit the IR radiations above absolute zero (-273 ^{o}C) temperature [13], and an infrared camera can detect the radiations from the defect regions, and convert the obtained information in image form (e.g. thermogram). In the day time solar irradiations heat up the concrete surface and the heat flows within the concrete by conductions [14]. Figure 1a shows the thermal response of subsurface defect in concrete for both day time and night time, while Figure 1b explains the thermal energy exchange between concrete bridge and surrounding environment during day and night time respectively. As shown in Figure 1a, during day time when a concrete structure exposed to solar radiation, since the delamination or air-filled voids have negligible thermal conductivity compared to the concrete, it can act as a thermal barrier so that the concrete above the defected areas has a relatively higher temperature than that of the sound area. In contrast, during time when there is no solar/heat radiation (i.e., cooling phase), the surface temperature of delamination region is relatively lower than that of intact concrete region, as the defect area radiates energy more quickly in night time[15]. This indicates the defect detection using infrared thermography can be carried out both in daytime and night The accuracy of delamination detection using IRT depends on several factors, such as the orientation and location of structure with respect to sun (radiant heating), the wind velocity, ambient environmental conditions, time for data collection and surface conditions [11].

The ASTM D4788-03, standard test method (2013) for bridge deck inspection using IRT [16] summarises the test procedure and environmental parameters that should be considered during the IRT test. For example, the rise in ambient temperature of 11.1 °C, after 4h sunshine on concrete deck surface or 6h sunshine for asphalt covered decks with wind speed less than 24 km/h will allow the accurate data collection for subsurface delamination during winter season. In addition, studies have indicated that the characteristics of the delamination, particularly the size of the delamination, affect the temperature gradient on the surface of the structures [17, 18]. For example, studies on the effect of solar irradiations and environmental variables on the defect detections suggested that 4-9 hours after sunrise is the best time for delamination detection [19-21]. In contrast, Seong et al. (2011) [22] revealed that, for delamination with 64mm deep, IRT detection during night time could produce a better results in comparison to day time. Furthermore, previous studies found that the time suitable for delamination detection is different for different parts of the bridge structures. For example, noon time is good for the bridge deck inspection whereas midnight is the favourable time for the soffit [23].

G. Washer et al.[20] studied the effect of solar irradiations on the vertical concrete block for long period of three months with different delamination depths. To overcome the effect of short term cloud cover or any other obstruction that can prevent direct irradiation of structure, they have estimated the total heat input into the system by integrating the heat flux over time and presented the results in term of solar loading (kW-hr/m^2), and concluded that a solar load greater than 0.7 kW-hr/m^2 over a course of day can result in at least 1°C thermal contrast between defected and sound surface, and the results are dependent on depth of the delamination. Using Finite Element analysis, the study of Hiasa et al. (2017) [10] showed that the size of delamination is the most critical parameter which affects the thermal contrast (ΔT), followed by thickness and volume of the delamination.

Previous studies [11, 19-23] have defined the suitable timeframe for the infrared thermography as number of hours of sunshine after sunrise, and different researchers have suggested different time due to various reasons. The critical parameters that significantly affect the IRT results are heat flux, wind velocity as well as the depth and size of delamination. Masashi et. al [24] has studied the effect of heating duration on thermal contrast and concluded that ΔT_{max} principally depends on the total heat input regardless of heating duration. Washer et. al. (2010) [20] calculated total solar load on a particular day, by integrating the heat flux (W/m^2) over the total flux duration and has observed a linear correlation between total solar loading (kW-hr/m^2) and maximum thermal contrast (ΔT). with a correlation coefficient R^2 = 0.75. They concluded that corelating the total solar loading (heat input) with maximum thermal contrast can compensate for the transient heat fluctuations.

Hiasa et al. (2017)[10] has performed numerical simulation for effect of different solar irradiance conditions and ambient temperature at different timepoints of the year and found that there is no significance effect of seasonal conditions on absolute contrast.

The wind speed surrounding a bridge is another important factor that affects the thermal contrast of the bridge deck. Although wind convection has a significant effect on low emissivity materials, it still has a notable effect on high emissivity materials (e.g. concrete) under low thermal contrasts[25]. Previous studies[19] found that the thermal contrast decreases with the increase of wind speed. This is due to the fact that wind can add or remove heat from the concrete surface depending on difference between the temperature of the bridge deck and ambient temperature[9].

Despite several studies in this area, it is not clear the ideal time of the day to carry out the IRT testing for bridge deck, and how ambient environmental conditions affect the measurement outcomes. This study aims to address these questions through performing experimental studies in conjunction with numerical modelling. Since ambient environmental conditions are highly dependent upon the solar position and radiation intensity, this study mainly focuses on the heat flux coming into the system as radiations and the wind velocities that create a significant impact on surface contrast through radiative and convective heat transfers, respectively. The study also focusses on the development of correlation between the total heat input and absolute thermal contrast, and instead of proposing a time span for thermal inspection a quantitative approach for suitable time of inspection using total heat input through radiations is proposed.

2. METHODS

2.1 *Experimental program*

2.1.1 Concrete slab casting

As shown in Figures 2-3, two reinforced concrete slabs were prepared for the experiment. The polystyrene Styrofoam were used to mimic the internal delamination as its thermal conductivity is very close to air (air: 0.0241W/m.^{o}C , polystyrene: 0.033 W/m.^{o}C), and therefore could produce similar impact on surface thermal contrast as of air voids[26]. As shown in Table 1 the depth and size of delamination are chosen such that the influence of the variation in area and depth on surface contrast could be investigated. The Slab 1 has a delamination area of 200 cm^2 with a depth of 63mm from slab surface, while Slab 2 has two delamination with area of 100 cm^2 each and located at 38mm and 63mm depth from surface, respectively. The sides of the slabs were insulated with the wooden formwork to ensure adiabatic state and imitate large concrete bridge deck.

2.1.2 Experimental procedure

As shown in Figure 4, at the beginning of each experiment, the environmental conditions (*i.e.* temperature, humidity and wind speed) were recorded using a Digitech Wireless Weather Station XC0348. The wind speed, generated by a fan with three power levels, was measured using a weather station, which was positioned away from the fan at the same distance between the slab and the fan. Four 500W halogen lamps were used to heat up the samples through thermal irradiations. The lamps were spaced such that a uniform heat flux could be created over the surface of slab. The heat flux (W/m^2) on the slab surface was measured using an RS Pro IM-750 solar power meter (Figure 4c). As shown in Figure 4a, the FLIR T1050sc infrared camera used for primary data collection was positioned on a stand at 1m above the slab, perpendicular to the surface to reduce angle induced errors. The image resolution of the camera was 1024 x 768 pixels at a frame rate of 30 Hz. Thermal sensitivity of camera was less than 20mK with a field of view 45^o x 34^o.

Slabs were heated up by the Halogen lamps under different wind velocities (Table 2) for a period of 60mins and then allowed to cool down for next 60mins. During the experiment, the FLIR T1050sc infrared camera was used to capture the thermal images on the surface of the slabs, which were further analysed using the FLIR ResearchIR software. The absolute contrast on slab surface, $\Delta T(t)$, can be determined by using obtained temperatures on the delaminated $T_d(t)$ and intact concrete areas $T_s(t)$ (Figure 5) as follows,

$$\Delta T(t) = T_d(t) - T_s(t) \qquad (1)$$

2.2 *Numerical Modelling*

2.2.1 Heat transfer theory

Governing equations

The heat transfer within the slab is governed by pure conduction which depends upon the thermal properties of the material, can be expressed by using Fourier's heat transfer differential equation,

$$\rho c \frac{\partial T}{\partial t} = Q' + \nabla . (k \nabla \mathrm{T}) \qquad (2)$$

where ρ is the density of material (kg/m^3), c is heat capacity at constant pressure (J/kg. K), k is the material thermal conductivity (W/m. K) and T is the absolute temperature (K), Q' is the internal heat generation rate (if any) (W/m^3) and *t* is time.

Boundary condition

The energy transferred between the slab surface and the surrounding environment is a complex phenomenon (depicted in Figure 1). The boundary conditions associated with the equation (2) can be expressed by following equation,

$$-\mathbf{n} k \nabla \mathrm{T} = \mathrm{q} \qquad (2a)$$

where q is the rate of the energy transfer at the surface of slab. It includes the radiations from source, the relationship between the slab and ambient environment as well as the thermal radiations from surface to the environment [27].

$$q = q_s + q_{con} + q_r \qquad (3)$$

Thermal energy due to radiations received by the concrete surface from heat source is given by

$$q_s = \alpha I \qquad (4)$$

where α *is* absorption coefficient of concrete surface, depends upon colour and texture of the surface as well as the wavelength of the radiations. *I* is the total radiation flux on the surface (W/m^2).

The heat transfer (lost or gain) through convection between the concrete surface and the surrounding atmosphere due to temperature difference can be described by using the Newton's law of cooling,

$$q_{con} = h_c\,(T_c - T_a) \qquad (5)$$

where h_c is convective heat transfer coefficient (W/(m^2.K)), T_c is the concrete surface temperature and T_a is the surrounding air temperature (K). Kelhbeck (1975) [28] has recommended an empirical formula to estimate the heat transfer coefficient for the concrete box girder as follow,

$$h_c = 3.83v + c \qquad (6)$$

where, c is constant which can be defined as 4.67 for top surface, 2.67 for bottom surface and 3.17 for vertical surfaces. The heat loss from the slab to surrounding environment through long wavelength radiation is given by,

$$q_r = \varepsilon(\sigma T_a^4 - \sigma T_c^4) \qquad (7)$$

where, σ is the Stefan-Boltzmann constant = 5.677 x 10 $^{-8}$ W/ (m^2 .K^4), and ε is the emissivity of the material which depends upon the surface condition and type of material and can also vary with the surface temperature and the radiation wavelength.

In case of the surface to surface radiations, in equation (7), $\sigma T_a^4 = G$ where G is the total incoming radiative flux and is called *irradiation*.

The system was initially considered in equilibrium under ambient environmental conditions. The ambient environmental temperature was taken as initial condition.

$$T_{initial} = T_{amb} = 24\ ^{o}C$$

The sides of the slab are taken as fully insulated (i.e, q = 0)

2.2.2 Numerical model development

This study presents a numerical model consisting of governing equations (1)-(7) which are solved numerically using Heat Transfer Module of commercial FEM package COMSOL Multiphysics[29]. First, the model predications were validated using experiment data obtained in this study. A series of parametric studies were then carried out to investigating the effects of the rate of heat flux on ΔT on the surface of bridge decks with the aim of identifying the optimal inspection times for different geometry characteristics of delamination.

To compare the model predictions with experimental results, the boundary conditions of the model were determined based on experimental conditions. For example, the heat flux coming from halogen lamps was measured on the concrete surface using an RS Pro IM-750 solar power meter (Figure 4c), the temperature and humidity was also captured. All these experimental measurements are input into the developed model as boundary conditions for predicting the absolute contrast on slab surface, ΔT(t). The geometry of the modelled slab is same as that used in the experiment. The thermal properties of the materials used in this study are obtained from previous studies [10, 30-33] and summarised in Table 3. The convergence study shows that the free tetrahedral elements with an element size ranging from 0.002m to 0.0275m can achieve a better outcome.

The heat flux from halogen lamps was simulated as an external radiation source in COMSOL Multiphysics. To attain the desired spectral distribution of electromagnetic radiations and heat flux on the surface of the slab, the source temperature, power and distance from the slab were adjusted accordingly. The surface of the slab facing lamps is modelled as “diffuse surface” to account for the radiation exchange between source and test slab.

3. RESULTS AND DISCUSSION

3.1 *Experimental results*

Figure 6 shows the obtained time-dependent thermal contrast for different areas and depths of delamination. It can be seen from Figure 6a that a large size of delamination generally leads to a relatively large thermal contrast. For example, the maximum thermal contrast of the delamination of 200cm^2 is three times higher than that of delamination of 100cm^2. In addition, the results in Figure 6b indicate that the thermal contrast resulting from a shallow delamination is generally higher than that of a deep delamination in heating phase, and the difference gradually decreases in cooling phase. The experimental observations are consistent with previous experimental studies [10, 11, 19, 20, 34].

Figure 7 shows the time-dependent thermal contrast under different wind velocities (Slab 1, depth 63mm and area 200cm^2). The test scenarios are shown in Table 2 with other environmental factors remaining constant (i.e. Humidity 40% and ambient temperature 24^{o}C). The sample was exposed to the radiant heat flux generated by the halogen lamps for first 60 minutes, then followed by the cooling phase for 60 minutes under ambient environmental conditions. The results show that a wind velocity has a considerable impact on the thermal contrast on the slab surface. The increase in wind velocity results in the decrease in the contrast as wind can take heat away from the surface. For example, compared to the case of no wind condition, the 25km/h wind speed can result in the decrease of thermal contrast by two-fold. It should be mentioned that, compared to no wind condition, a small velocity of wind 5km/h can cause a significant drop in surface thermal contrast, and the rate of drop in thermal contrast gradually reduces with the increase in wind velocity. In addition, effects of wind become significant during the cooling phase when there is no input heat flux.

Figure 8 shows the effects of wind velocities on target surface thermal contrast for different delamination depths. It shows that the detection of deep delamination is significantly affected by the wind speed since the energy is rather difficult to reach the deep defect zone in concrete under windy condition. For example, an increase in wind velocity from 0km/h to 15km/h could make thermal contrast almost undetectable for a 63mm deep delamination, however, for a comparatively shallow delamination, (i.e. 38mm), the change in thermal contrast is not so significant. The results from Figures 7 & 8 demonstrate that the important role of wind speed plays in delamination detection using IRT, and a threshold wind speed of 24 km/h is recommended by ASTM D 4788-03[16].

3.2 *Model validation*

Figure 9 compared the model predictions with the experimental measurements. The purpose of experimental studies conducted in present study is to validate the numerical model developed in this study. After validation, the numerical model is implemented to investigate the effects of the rate of heat flux on ΔT on the surface of bridge decks with the aim of identifying the optimal inspection times for different geometry characteristics of delamination (i.e. size and depth). Figure 9a, shows the experimental heat flux model where a slab was irradiated with a uniform heat flux of 220 W/m^2 for 60 minutes, and then followed by 60 minutes cooling under ambient environmental conditions with no wind blowing over the surface of concrete. The number 220 (W/m^2) was a randomly achieved uniform heat flux over the entire concrete surface by adjusting the position of halogen lamps. The surface temperature was recorded using IR camera and absolute thermal contrast was obtained by equation (1).

For numerical simulations the generated heat flux was modelled in COMSOL as external radiation source for 60 minutes and then allowed for 60 minutes of cooling. Figure 9b compares the numerically predicted absolute thermal contrast comparison for 63mm deep delamination to the experimental results, while Figure 9c shows the surface temperature comparison between numerical prediction and experimental results. It can be seen that the numerical predictions agree the experimental results reasonably well.

3.3 *Numerical parametric studies*

After validation, the proposed model is implemented to conduct a series of parametric studies. As discussed in introduction, studies [11, 19-23] have defined the suitable timeframe for the infrared thermography as number of hours of sunshine after sunrise. Several inconsistencies have been found in the results. The IRT results are significantly affected by heat flux, wind velocity as well as the depth and size of delamination. Some researchers'[10, 20, 24] have identified that different radiation intensities has no significant effect on thermal contrast development however, total heat input governs the relationship. Therefore, it would be of great importance to understand the correlation between total heat input and generated absolute thermal contrast through numerical simulations and find out that minimum amount of input heat energy which can generate a thermal contrast easily detectable (safe detectable) by a normal range IR camera. In this way, instead of proposing a wide time span of a day for thermal inspections, one could reasonably predict the best possible time for thermographic inspection of the assets by just knowing the forecasted environmental parameters (e.g. radiation intensity, cloud and wind conditions) for a specific day. The developed correlation between total heat input and thermal contrast could compensate for the difference in short-term local heat disruption and solar intensity due to different geographic locations and seasonal variations, and thus provides a uniform and quantifiable approach for passive thermographic inspections. The safe detectable absolute thermal contrast is taken as 1^oC in this study. Although the ASTM D4788-03 [16] recommended minimum thermal contrast (i.e., safe detectable) is 0.5 ^oC however, as seen in Figure 8b the wind can drop the thermal contrast up to 50%.

The values of model parameters used for parametric study are summarized in Table 4. The total heat input (Q) applied to the system is varied from 220W-hr/m^2 to 900 W-hr/m^2 under two different heat flux rates (heating rate) and heating durations (i.e, Case 1 being higher heat flux rate (q_s) and short heating duration (t_h), whereas Case 2 for low heat flux rate (q_s) and longer heating duration (t_h)). The values of thermal parameters are chosen such that, it could be closely associated with the diurnal solar radiation variation. Also, the hourly average was preferred as the results are intended to present guidelines for real field inspections. To incorporate the effect of geometric parameters of defects (*i.e.* size and depth), different geometric parameters are defined (Table 4b) for the above described parametric heating conditions. The defect parameters were defined, such that it should be corelated with the real field structures. For example, the delaminations in reinforced concrete normally appears near the rebars. And for conventional reinforced concrete bridge decks the rebars usually lie at a depth of 25 to 65mm.

Although the peak absolute thermal contrast happens in the early stage of the cooling phase (Figure 9(b)), the thermal contrast at the end of heating period is considered as maximum thermal contrast (ΔT) and the increase in ΔT during cooling phase is taken as supplementary input to avoid the uncertainties due to unquantifiable correlation between heat input and thermal contrast rise.

3.3.1 Numerical results

Figure 10a shows the relationship between total heat input (Q) and absolute thermal contrast (ΔT) for different depths of delamination under two different heat flux rates and heating durations (Table 4). It can be seen that the absolute thermal contrast has a positive linear relationship with the total heat input (Q). The rate of increase in ΔT with Q varies with the depth of delamination, ΔT is more sensitive to Q for a relatively shallow delamination than that for a relatively deep delamination. Furthermore, the heat flux rate plays an important role in developing ΔT on concrete surface. As shown in Figure 10a, under the condition of same depth and equivalent total heat input, the developed absolute thermal contrast is different for Case 1 (higher heat flux rate) and Case 2 (low heat flux rate), especially when the defect depth is relatively shallow (e.g. z=25mm). However, with the increase in depth of delamination, this difference gradually diminishes.

Most importantly, Figure 10b shows the total amount of heat input required to generate an absolute thermal contrast of 1 ^{o}C (safe detectable ΔT) as a function of depth for two heating cases (i.e. Case 1 and Case 2). It can be seen that, under two different heat flux rates, there is almost two folds difference in total heat input for a shallow delamination (i.e. z=25mm) and this difference gradually disappears with the increase of defect depth. Hence, for a relatively deep delamination, the generated thermal contrast is majorly dependent upon the total heat input and heat flux rate and duration has less impact on ΔT. Although a moderately shallow defect can be detected using IRT after exposure to intensive heat over a short period of time, previous studies have shown that flash thermography for IR inspection is effective for defect detection in thin structural members (e.g. wind turbines) [24, 35-38]. As the present study mainly focuses on delamination detection in concrete members of bridges which are generally over 200mm thick, a relatively long period of time exposure to direct solar radiation could make the IR inspection more effective.

Figure 10c shows the total heat input required to generate absolute thermal contrast of 1^{o}C for different delamination sizes under two different heating rate and heating durations (z = 50mm). It shows that relatively large total heat input (Q) is required to detect a relatively small delamination size (e.g. 50cm^2), and the required Q in Case 2 is larger than that in Case 1. In addition, for a relatively large delamination size (e.g. 300cm^2), much lower Q is required to detect the defect and there is little difference in Q required under Case 1 and Case 2.

The total heat input Q is plotted as a function of square of depth (z^2) in Figure 10d. It is revealed that Q and z^2 has a strong positive linear relationship (R^2 = 0.99) in both Case 1 and Case 2. Previous studies [38-42] on defect depth detection based on the time required to reach the peak thermal contrast ΔT_{max} need to continuously monitor the target of interest for a long period of time. The relationship between total heat input with the depth of delamination developed in this study could provide an effective way for estimating the depth characteristics of a defect.

4. CONCLUSIONS

Although Infrared thermography (IRT) is a useful tool for quick scanning of subsurface defects in reinforced concrete bridge decks, this technique is very sensitive to the environmental Condition. In this study, effect of a range of environmental parameters (e.g. wind velocity and radiant heat flux) on defect detection using IRT has been investigated experimentally and numerically. The following are the major conclusions:

- The wind has a significant impact on absolute thermal contrast (ΔT) development. With an increase in wind velocity thermal contrast decreases. The rate of drop of thermal contrast is much higher for low wind velocities as compared to higher wind velocities. The impact of wind on thermal contrast increases with the increase in depth of delaminations from surface.
- This study presents a numerical model for investigating the effects of critical parameters (e.g. geometry of delamination and environmental conditions) on the IRT measurement results. The model predictions agree reasonably well with experimental data.
- The thermal contrast ΔT generally increases with the increase of total heat input (Q). However, the heat flux rate and duration can potentially influence the thermal contrast under different geometry characteristics of delamination.
- By looking into the effect of wind velocities and ASTM D4788-03 existing recommendations, a value of 1^{o}C is taken as a safe minimum detectable thermal contrast. To generate absolute thermal contrast of 1^{o}C, a larger Q is required for a relatively shallow delamination (e.g. two-folds difference when z=25mm) under a lower heat flex rate. With the increase of delamination depth, the difference of ΔT resulting from the higher heat flux rate and the lower one gradually diminishes.
- There is a linear relationship between the square of the depth (z^2) and total heat input (Q) required to generate absolute thermal contrast of 1^{o}C (R^2=0.99).
- To generate absolute thermal contrast of 1^{o}C, a larger Q is required for a relatively smaller delamination (e.g. 50% difference when A=25mm^2) under a low heat flux

rate. With the increase of delamination size, the difference of Q resulting from the higher heat flux rate and the lower one gradually diminishes (e.g. A=300mm^2).

- The thermal contrast development is more dependent upon the total heat energy absorbed by the system rather than the heating duration or heat intensity independently. Therefore, instead of suggesting number of hours of sun light required to generate thermal contrast, a correlation between total solar energy absorbed by the slab and thermal contrast has been developed and it was found that a total heat input of 0.68 kW-hr/m^2 from sun is enough to generate a thermal contrast of 1^{o}C or higher (safe detectable) for up to 63 mm deep delamination.

5. ACKNOWLEDGMENTS

The authors wish to thank the Australian Research Council (ARC IH150100006), and CRC Bushfire & Natural Hazards. The authors would also like to thank Higher Education Commission Pakistan (HRDI- faculty development of UESTPs-UETs phase-1) and The University of Melbourne for their support.

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