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Research paper

Building condition ratings using infrared thermography: a preliminary study

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Abstract: Deterioration and defects in building components are key aspects to consider when assessing buildings' conditions, as they may influence the building's functionality. The typical defects include cracking, moisture, dampness, and architectural defects. This paper aims to evaluate the defects in a building using a non-destructive testing (NDT), which is the Infrared Thermography (IRT) method. A visual inspection method is then conducted to verify the results of the IRT method. The combination of IRT and visual inspection methods can identify the type of defect and level of severity more accurately. In both methods, ratings or scores are given to the collected defect data to determine the consistency between them. Two (2) buildings were selected as case studies; AA1 and BB2 are multi-storey buildings. From those, 51 and 67 spots were taken from the IRT method and further verification process, respectively. Among the defects that were found were moisture, dampness, cracking, staining, chipping, and flaking paint. From all the findings, IRT was found to be comparable with the visual inspection results for serious defects such as cracking and flaking paint. However, IRT was believed to underestimate the architectural defects of staining and chipping. Even so, serious defects such as dampness were also underestimated in IRT due to the fact that the temperature difference between

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different ratings will not differ much. In conclusion, the IRT method has the potential to be used as a tool for building condition rating. However, it should be assisted with a visual inspection, and more research needs to be conducted for its practicality.

Keywords: non-destructive testing (NDT), Infrared Thermography (IRT), visual inspection method, ratings, defetcs

1. Introduction

According to Jędrzejczyk et al. [1], periodic inspection and assessments of structural condition are conducted in order to sustain a building's structure at the proper level and appropriate technical efficiency, which forms the basis for restoration work . There are many assessment methods to determine the condition of structures such as visual inspection with a rating system [2], risk-based assessment with fuzzy statistics [3, 4], and seismic risk assessment [5]. In addition, the most advanced assessment method is technology-based called building information modelling (BIM). The application called MWBIM (Map of Knowledge BIM) will gather information regarding detected construction flaws, their documentation, and maintenance using BIM technology [6]. However, the most common method to determine the condition of structural buildings is visual inspection with a rating system. The conventional method utilizes visual inspection, which depends on the inspectors' skill, experience, and building condition decisions [7]. The inspectors will evaluate the building components based on the defects and deteriorations using a condition rating [8]. They will rate based on the defects and deteriorations that they found such as staining surface, chipping paint, discolouration, cracking, spalling, moisture, dampness and faulty electrical. Nevertheless, previous research has proven that subsurface defects are the primary cause of structural damage if not identified and repaired [9]. It is very important to discover all defects and deterioration with respect to the building so that the safety and serviceability of the building can be evaluated to determine its performance [10].

According to prior research, infrared thermography (IRT) is one of the non-destructive methods used to assess buildings such as historical buildings [11], office space [12] and concrete bridge [13, 14]. It depends on imaging the difference in heat radiation of objects to detect heterogeneities in a concrete structure [7]. Infrared thermography (IRT) results can be used to determine the state of structures, rank them according to their current state, and compare various attributes using threshold values. Simple, easily available technology and quick operational approaches are the reasons why IRT should be used. When it comes to assessing the building, the implementation of inspection frequently encounters difficulties. There are many activities going on in the building and therefore the use of IRT tools can speed up the inspection process and so meet the requirements of the building assessment to be completed.

In general, buildings can be evaluated based on external and internal conditions [15]. The meaning of external circumstances is understood in the context of the comfort and naked eye view seen by the user and outsiders. The internal state, on the other hand, is the circumstance in which each component of the building is assessed based on the real state of defects. In this paper, the potential of using IRT to detect the internal condition of the building is explored that can enhance the standard practice of building inspection by using visual inspection alone. The combination of IRT and visual inspection methods can identify the type of defect and level of severity more accurately. The research was carried out in the context of assessing the state of the building in relation to its surroundings in a tropical climate. For a tropical country, the environmental conditions are consistently wet and humid with temperatures ranging from 25°C to 34°C [16]. Thus, the scope of building condition rating in the aspects of the exterior of the building, such as the external walls of rooms and bathrooms, is examined in this study.

2. Literature review

2.1. Building defects

According to Bakri and Mydin [17], building defects are an important issue requiring proper attention. It can occur in a new or existing building. Ismail et al. [18] stated that building defects are called "capacity failures" or "mistakes" in tenant building guidelines or criteria. Building defects exist in two types, namely structural and non-structural. The structural defects that occur in reinforced concrete structures are cracking, delamination, and spalling. Non-structural defects typically occur in building finishes such as moisture, dampness, leaking, fungi, and moss. Olanrewaju [19] justifies that a building defect has an impact on the structures or their combinations on usability, performance, acceptance, or appearance. The building defects can become more severe if they are not addressed properly on time and may affect the strength and integrity of the adjourning components, elements, and building parts, or in a worst-case scenario, may cause the structure's failure and collapse. Any defect in a structural element of a building is caused by a variety of factors, including the environment [16], poor craftsmanship, and improper design [17, 20].

2.2. Building condition rating standard technique: visual inspection

Visual inspection is a valuable assessment method in every investigation supported by typical optical tools [21]. Visual inspection is the most basic and common test, which saves time and money by minimizing the number of further tests required [22, 23]. However, most researchers suggest that visual inspection should combine with NDT to get reliable results to prevent subsurface defects or structural collapse [21, 24]. The other advantage of visual inspection is that it does not require expensive equipment. The disadvantage of visual inspection is that it is limited to subjective qualitative analysis because it depends on the assessor's knowledge and experience [25]. This statement is also previously discussed by J. H. Bungey et al. [21], which states that visual aspects could be associated with workmanship, structural serviceability, and material deterioration. To comply with that, the engineers must be able to distinguish between numerous types of defects that may be discovered during the inspection process.

The assessor needs to prepare a checklist with a rating system to evaluate the building's condition. The building conditions can be evaluated based on rating and it can differ depending on the assessors and guidelines that they use. An example of the reference is using a three-point colour-coded building rating, starting from 1 – minor defects, corresponding to present some risks to building function, and ending at 3, critical defects, corresponding to life-threatening to resident [26]. In addition, a visual inspection cannot detect internal structural abnormalities until they have progressed to the point where they cause visible symptoms that are undesirable and should be avoided [13].

2.3. Technology based condition assessment using infrared thermography

According to Kashif Ur Rehman et al. [14], engineers mostly used non-destructive test (NDT) instruments to provide cross-checking information on structural integrity. NDT can be used on structural components such as construction buildings, historical buildings, and bridges. Infrared thermography (IRT) is one of the non-destructive tests used in structural and building inspection. Application of IRT to assess the building condition of a building in operation is a promising approach. The IRT is a well-known non-destructive test for cost-effective, precise, and practical evaluation of building components quality, heat loss through windows, and subsurface defects [27,28]. Gholizadeh [22] found other advantages of IRT, such as a large building component can be inspected and it may be done individually. The building conditions can be evaluated faster and more accurately, provided the analysis process from the IRT findings is conducted quantitatively and systematically. The existence of numerous components in the structure necessitates the meticulous execution of the systematic analytical procedure. The necessity for costly instruments and qualified inspectors to operate the instrument are drawbacks of this inspection.

According to Barreira, Almeida and Ferreira [29], Preda and Scurtu [12], Mac et al. [30], infrared thermography (IRT) works with the long infrared of the electromagnetic spectrum, which means it detects radiation and temperature. The output image is called thermograms. The IRT can detect both visible and non-visible surfaces because all objects that radiate infrared radiation have a high surface temperature. In the image of IRT, which is thermograms, the user can see many temperature variations. The amount of radiation that is transmitted by an object increases with temperature. The display image of thermograms will show the warm and cool temperatures in different colours because of the infrared energy emitted from the objects. Hence, it is easy to see the object against the environment, day or night, because the cooler backgrounds in the thermal imaging camera stand out well against the warm objects [29].

Infrared thermography is an extremely sensitive non-destructive test when it comes to environmental factors such as sunlight (temperature), relative humidity, and wind [7, 13]. Sunlight is the main force to create thermal gradients since it has an impact on the measured temperature values and provides thermal energy to concrete. The increase in surrounding temperature triggers a rise in the temperature of the building component; otherwise, events such as humidity, rain or snow lower the temperature of the building component. If temperature variations are greater during the day, thermal gradients may increase [31]. High wind speeds can lower the temperature of building components due to the temperature-cutting effects generated on the surface [32].

Lo and Choi [15] stated that the structural defects such as delamination, cracks, and spalling create a small air void on the underneath of the structure, which prohibits heat from flowing between the void and the core structure. Under the heating from the sun, the defective area consequently shows a greater temperature than the unaffected area, resulting in “hot spots” in the IR thermograph. Jadin and Taib [33] pointed out that electrical faults are known as non-structural defects caused by abnormally high electrical resistance and also produce “hot spots” in the IR thermograph. Then, Lo and Choi [15] indicated that non-structural defects such as dampness, moisture, moss, and fungi occur when the part of damp area loses heat energy much faster than the dry areas because damp is a greater conductor of heat energy than an air void. The heat is detected using IR thermography, which recognises this pattern of unequal heat dissipation, and the damp areas will have a different surface temperature profile (i.e., cold spots) than the surrounding dry areas. Based on the previous researches, the depth range of defect detection falls to around 50–100 mm from the surface [34, 35].

According to Jadin and Taib [33], the severity level assessment using infrared thermography (IRT) is evaluated based on the temperature difference. The temperature difference between the anomaly and its surroundings is one of the most commonly used [36]. According to Jadin and Taib [33] and Bauer et al. [37], the temperature difference between the anomaly and its surroundings is calculated as $T = T_2 - T_1$ based on the T method, where T_2 denotes the highest temperature in Area 2 or at Point 2, whereas T_1 denotes the highest temperature in Area 1 or at Point 1, which is designated as the ambient temperature. Table 1 shows the severity level of defects based on temperature variation. Then, maintenance action is required according to the priority level.

Table 1. Level of severity with recommended action

Author	Priority scale	ΔT with recommended action	Scope
[38]	1–3	Rating 1: 1–3°C: Possible deficiency Rating 2: 40–15°C: Indicates probable deficiency Rating 3: > 15°C: Major discrepancy	Electrical fault
[12]	1–3	Rating 1: 1–10°C: Minor Problem Rating 2: 10–15°C: Average Problem / Need Physical Inspection Rating 3: 15–20°C: Critical Problem / Immediately Repair	Typical defects / all types of defects
[40]	1–2	Rating 1: 2°C: abnormal behaviour Rating 2: 4°C: Indicates probable deficiency	Typical defects / all types of defects
[7]	No	0.8°C (Min): abnormal behaviour	Typical defects / all types of defects
[39]	No	0.5°C (Min): abnormal behaviour	Typical defects/ all types of defects

3. Research methodology

In this study, two (2) reinforced concrete buildings have been selected as case studies. The buildings are multi-story buildings and in operation as a hostel or accommodation. The details of the building are summarized in Table 2. Meanwhile, Figure 1 shows the picture of the case studies.

Table 2. Details of case studies

Criteria	Case Study 1	Case Study 2
Building Reference	AA1	BB2
Type of building	Reinforced concrete	Reinforced concrete
No. of stories	Five (5)	Five (5)
Function of building	Accommodation	Accommodation
Floor area, m^2	817.384	817.384
Age of building, years	30	30
No. of IRT spots	51	67
Location of IRT spots	A, B, C, D, E, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, AA, AB, AC, AD, AE, AG, AH, AI, AJ, AK, AL, AM, AN, AO, AP, AQ, AR, AS, AT, AU, AV, AW, AX, AY	A, B, C, D, E, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, AA, AB, AC, AD, AE, AG, AH, AI, AJ, AK, AL, AM, AN, AO, AP, AQ, AR, AS, AT, AU, AV, AW, AX, AY, AZ, BA, BB, BC, BD, BE, BG, BH, BI, BJ, BK, BL, BM, BN, BO, BP, BQ

Building AA1 Building BB2

Fig. 1. Actual view of the case studies

The two buildings, AA1 and BB2, were inspected using thermal infrared testing as an NDT type of test. The two buildings are student accommodations located in Malaysia.

Malaysia is part of a tropical country, with average temperatures ranging from 21°C to 32°C. It was reported that the temperature when conducting the study varied from 25°C to 32°C, and it is sunny weather at that time. The inspection session begins at 10.00 am and ends at 2.00 pm for six days. The defects such as cracking, spalling, delamination, moisture, peeling, flaking and chipping are considered as a scope in this study. The thermal infrared testing has been used to assess the conditions of the building envelopes and being later summarized in a form of building conditions. The verifications to the NDT findings is made using the condition rating from the visual inspection. In the NDT process, building images were taken using a Fluke IRT device with different spots of the building. The Fluke IRT using a 7.5 µm to 14 µm infrared band spectrum spectral band. The IRT concept was applied by producing a visual image from a thermal radiation pattern. The thermogram image was identified from the temperature difference, which is suitable for a building inspection or assessment. The Fluke IRT equipment was used to capture the image of buildings within a safe distance of the building envelope. The different amounts of infrared radiation are emitted by buildings' structures and temperature differences in visual images. The operating temperature of the Fluke IRT is a −10°C to +50°C and the resolution is 320 × 240 (76,800 pixels). During the process, 51 and 67 spots have been collected at the building envelopes of building AA1 and BB2, respectively. Figure 2a shows the position of thermal camera spots were taken at building AA1. Meanwhile, Figure 2b shows the position of thermal camera spots were taken at building BB2.

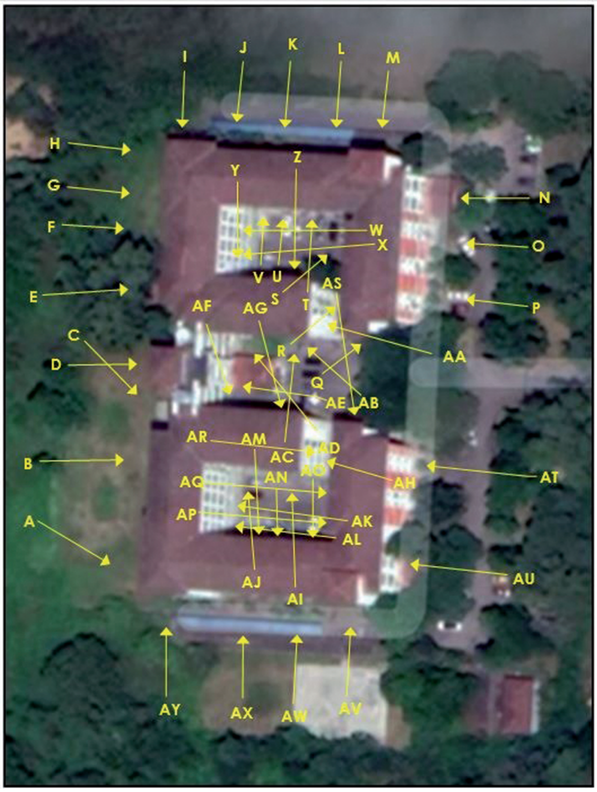
Once the thermal images were taken, they were introduced in the Smart View program, where the temperature parameters, relative and reflected apparent temperature were adjusted. All images can be adjusted by doing the level span scale for better visualisation. Later, visual inspection is conducted to verify the findings from the IRT. Visual inspection was conducted to the case studies and summarized in a form of a condition rating. The condition rating system is used to determine the current condition of building envelopes. A tool such as checklist was used according to the standard for registering the information of the building, identification, characterisation, defects in functional element and evaluation of condition of defect. The scope of the assessment is similar to the NDT evaluations.

The defects are assessed using three-point scale as proposed by a guideline: score 1 (minor defects), grade 2 (serious defects), Grade 3 (Critical defect) [26]. Table 3 shows the intensity of defects score for building assessment. Finally, the results from IRT were compared with the visual inspection results to find the consistencies between both methods. Figure 3 shows the research methodology designed.

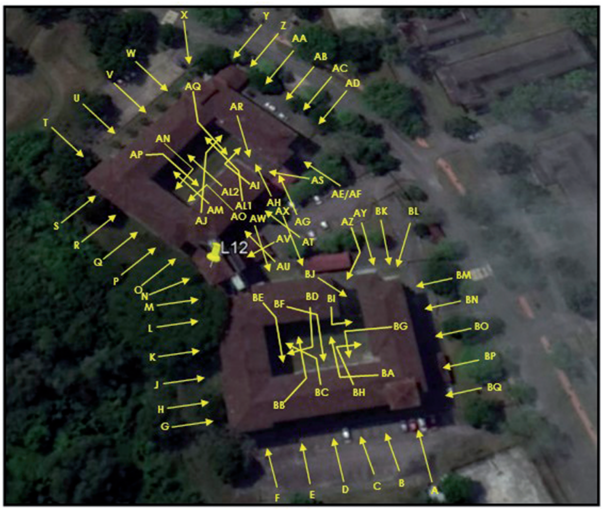
4. Results and discussion

4.1. Case study AA1

Figure 4 shows an example of the IRT findings that were obtained from the AA1 block of the case study. It shows a surface with temperature variations, where defects can be detected from the temperature difference. All 51 spots were analysed to determine their temperature



(a) Building AA1



(b) Building BB2

Fig. 2. Location of spots for IRT

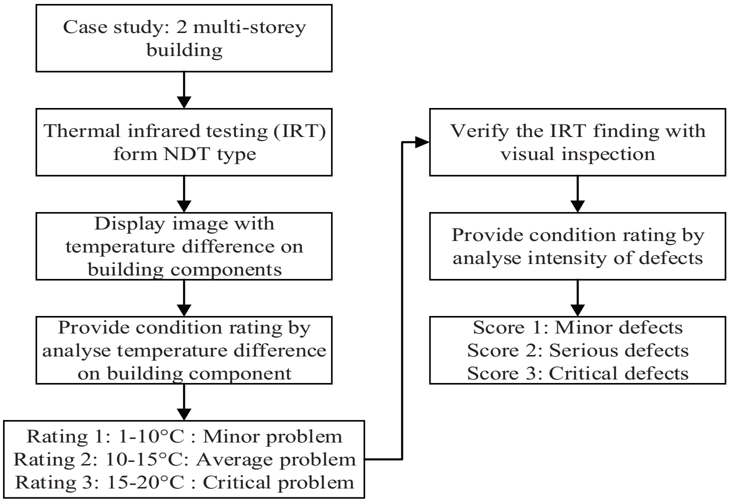


Fig. 3. Research methodology

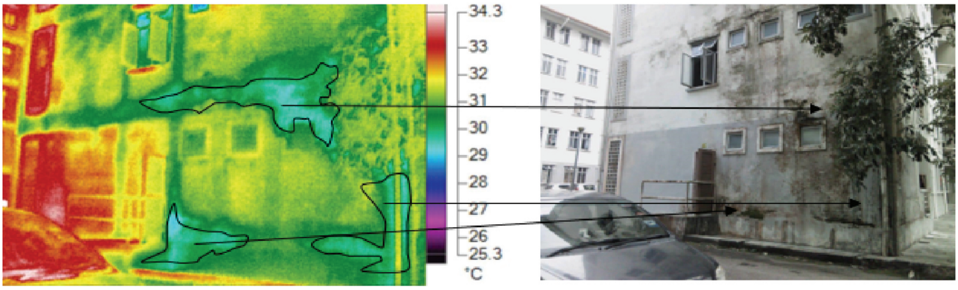
Table 3. Intensity of defect score [26]

Defect intensity	Description	Score
Minor	The defects in the residential units are visible and present. They pose some dangers to the building's function.	1
Serious	The defects have evolved to the point that they have harmed the building's functionality and inhabitant living circumstances.	2
Critical	The defects have reached their apex and are nearing the end of their useful lives. They are potentially fatal.	3

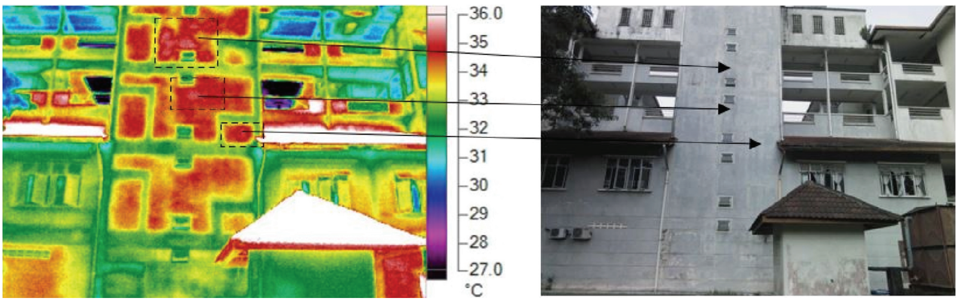
difference and their associated IRT rating. Meanwhile, Table 4 shows the overall results for the IRT method and visual inspection for the AA1 block of case study. From the results, IRT gave $\Delta T = 0$°C for 23 spots that gave no rating to the building envelopes. However, the visual inspection gives a score of 1, which indicates that there is an existence of a defect, which is the chipping paint and staining surface. It shows that the IRT cannot detect the chipping and staining surface defect as part of the temperature difference. However, it is believed that the defect, while observable, will not risk the building's functions. From the 51 spots, 28 spots were rated as having a rating of 1, which indicates a temperature difference of $4°\text{C} \leq \Delta T \leq 6°\text{C}$. Further verification was carried out, and it was discovered that there were defects of moisture, pigmentation and shrinkage cracking on the surface, resulting in a rating of 1. In addition, a rating of 2 was assigned to the spots due to shrinkage cracking with joint crack and dampness.

Table 4. Findings for IRT and visual observation for block AA1

Total area with defects	Location	Spots	Range of temperature	IRT analysis	IRT rating	Visual observation	Visual rating	Remarks
18	External wall – bathroom	2	Min: 28°C Max: 28°C	ΔT = 0°C, there are no abnormal behaviour at the building components.	N.A	Staining surface	Score 1	Discolouration (dark stain) with fungi on components.
		1			N.A	Pigmentation and staining surface	Score 1	Discolouration (dark stain) at the components.
		3	Min: 32°C Max: 36°C	Red spot occurs with ΔT = 4°C, there are abnormal behaviour at components	Rating 1 $\Delta T \leq 10$°C	Cracking	Score 1	Shrinkage cracking was observed.
		5	Min: 28°C Max: 32°C	Blue spot occurs with ΔT = 4°C, there are abnormal behaviour at the building components.	Rating 1 $\Delta T \leq 10$°C	Moisture	Score 1	Moisture was found at many places at this location. This location is prone to moisture and humidity especially when all water plumbing and piping pivot to those locations.
		1				Cracking	Score 2	Shrinkage and joint cracks were observed.
		6	Min: 26°C Max: 32°C	Blue spot occurs with ΔT = 6°C, there are abnormal behaviour at component	Rating 1 $\Delta T \leq 10$°C	Dampness	Score 2	High humidity at this location due to moisture pivot to that location.
33	External wall – room	10	Min: 32°C Max: 32°C	ΔT = 0°C, there are no abnormal behaviour at the building components.	N.A	Fading surface	N.A	There are many surfaces that have been faded
		10			N.A	Chipping paint	Score 1	Some spots show the paint begins to chipping (in early stage). Since the location is at the room, it is observed that the chipping is caused by the rain-water damage to the wall surface.
		8	Min: 32°C Max: 36°C	Red spot occurs with ΔT = 4°C, there are abnormal behaviour at components	Rating 1 $\Delta T \leq 10$°C	Cracking	Score 1	Shrinkage cracking was observed.
		5	Min: 28°C Max: 32°C	Blue spot occurs with ΔT = 4°C, there are abnormal behaviour at components	Rating 1: $\Delta T \leq 10$°C	Staining surface and dampness	Score 2	Surface stain and moisture was observed at random spots throughout the location.



(a) Bathroom location



(b) Room and common area

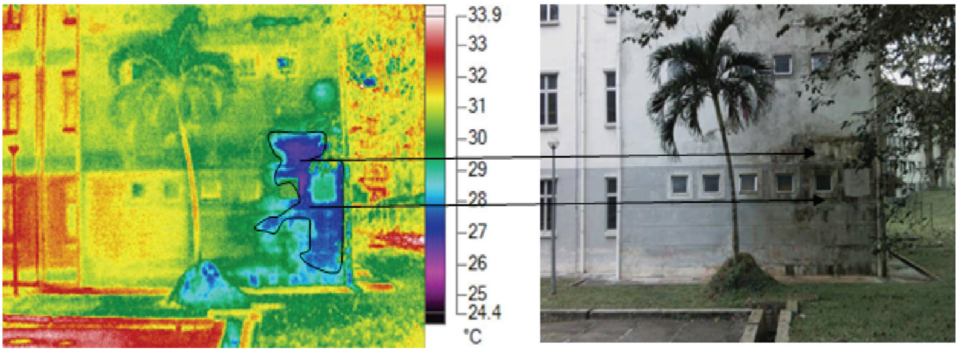
Fig. 4. Examples of IRT findings at the respective block AA1

4.2. Case study BB2

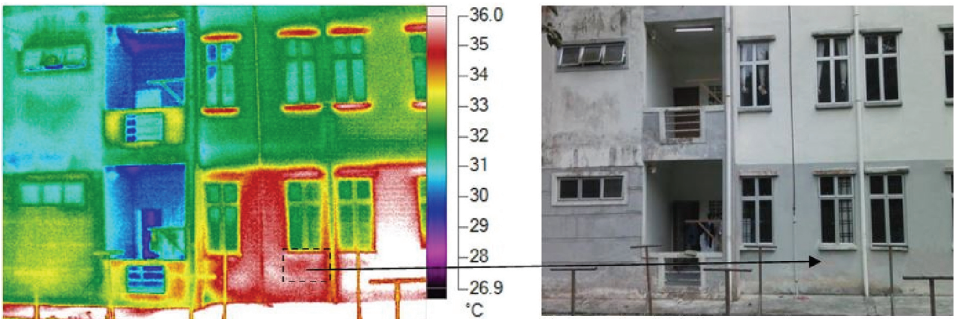
Figure 5 shows an example of the IRT findings that were obtained from the BB2 block of the case study. All 67 spots were analysed to determine their temperature difference and their associated IRT rating. From the results, IRT gave $\Delta T = 0°\text{C}$ for 27 spots that gave no rating to the building envelopes. However, the visual inspection gives a score of 1, which indicates the existence of a defect, which is the flaking paint. It shows that the IRT cannot detect the flaking defect as part of the temperature difference. However, it is believed that the defect will not affect the building's functions as it is still observable and will not impair its functions. From the 67 spots, 40 spots were rated as having a rating of 1, which indicates a temperature difference of $4°\text{C} \leq \Delta T \leq 7°\text{C}$. Further verification was carried out, and it was discovered that there were defects as a staining surface and dampness, resulting in a rating of 2 but only shrinkage cracks, which were indicated as a rating of 1. Therefore, it shows that the IRT method still underestimates the defect rating. However, it shows a maximum temperature difference of $\Delta T = 7°\text{C}$, approaching 10°C.

Table 5. Findings for IRT and visual observation for block BB2

Total area with defects	Location	Spots	Range of temperature	IRT analysis	IRT rating	Visual observation	Visual rating	Remarks
23	External wall – bathroom	2	Min: 25°C Max: 25°C	ΔT = 0°C, there are no abnormal behaviour at the building components	N.A	Fading surface	N.A	Discolouration of the paint was observed.
		5	Min: 32°C Max: 36°C	Red spot occurs with ΔT = 4°C, there are abnormal behaviour at components	Rating 1: $\Delta T \leq 10$°C	Cracking	Score 1	Shrinkage cracking was observed.
		8	Min: 28°C Max: 32°C	Blue spot occurs with ΔT = 4°C, there are abnormal behaviour at component	Rating 1: $\Delta T \leq 10$°C	Staining surface and dampness	Score 2	Surface stain and moisture was observed at random spots throughout the location.
		8	Min: 25°C Max: 32°C	Blue spot occurs with ΔT = 7°C, there are abnormal behaviour at component	Rating 1 $\Delta T \leq 10$°C	Staining surface and dampness	Score 2	Surface stain and moisture was observed at random spots throughout the location.
44	External wall – room	10	Min: 32°C Max: 32°C	ΔT = 0°C, there are no abnormal behaviour at the building components.	N.A	Discolouration	N.A	Discolouration of the paint was observed.
		10			N.A	Fading surface	N.A	Some spots show faded surfaces.
		5			N.A	Flaking paint	Score 1	Some spots show paint that has been flaked.
		9	Min: 32°C Max: 36°C	Red spot occurs with ΔT = 4°C, there are abnormal behaviour at components	Rating 1: $\Delta T \leq 10$°C	Cracking	Score 1	Shrinkage cracking was observed.
		10	Min: 28°C Max: 32°C	Blue spot occurs with ΔT = 4°C, there are abnormal behaviour at component	Rating 1: $\Delta T \leq 10$°C	Staining surface and dampness	Score 2	Surface stain and moisture was observed at random spots throughout the location.



(a) Bathroom location



(b) Room

Fig. 5. Examples of IRT findings at the respective block BB2

5. Conclusion

Based on the results of this study, it was concluded that the NDT techniques (IRT method) are useful in determining a building's condition rating. In this sense, IRT method can improve the standard practise of building inspection by using visual inspection alone. The IRT instrument used thermal infrared to allocate the defects in the building at the fastest rate as compared to the visual inspection. The thermal image produced by IRT has contours of different temperatures. If the cold spot is in the thermal image, moisture, humidity, or dampness can be determined. Meanwhile, if the hot spot in the thermal image is discovered, the void-based defect (such as cracking) can be discovered. The data obtained by IRT helps access the building's condition based on scientific data from the temperature variation, but it needs to be further assisted by the visual inspection. This is also found in this research project when the IRT method has limitations, especially for architectural defects such as faded surfaces, serious dampness and cracks with small openings. These defects, if not verified by the visual inspection, may cause the inspection process to misinterpret the actual condition of the building. There are a few recommendations for future studies, such as (1) describing defects in terms of depth and size from the IRT; (2) the influence of different environmental factors on IRT results, such as temperature, wind speed, and humidity; and (3) the effect of concrete age on defect detection in IRT.

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