Efficient Bridge Deck Inspection and Assessment Framework Utilizing Image-Based Non-destructive Evaluation Methods

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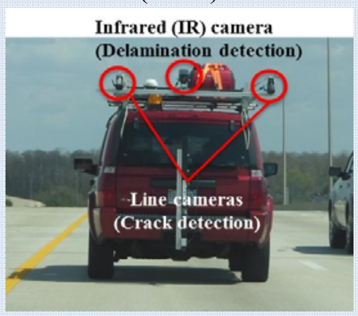
Ultimate Goal of Our Project: Image-Based SHM

SHM at Local Level

(Deck)



IRT & HD system
Short period (e.g. every year)

(Superstructure, Substructure, Culvert, Railing, etc.)

IRT & HD system
Middle period (e.g. every 3 years)

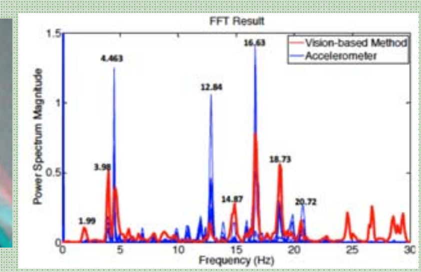
(Whole bridge, detailed inspection)

Sounding & visual/comprehensive techniques
Long period (e.g. every 6 years)

Decision Making

Keep monitoring, Maintenance, Repair, Rehabilitation, Replace, etc.

SHM at Global Level



GSHM w./ HD cameras

Implementation of efficient & effective bridge inspection
by integrating image-based techniques as complementary approach

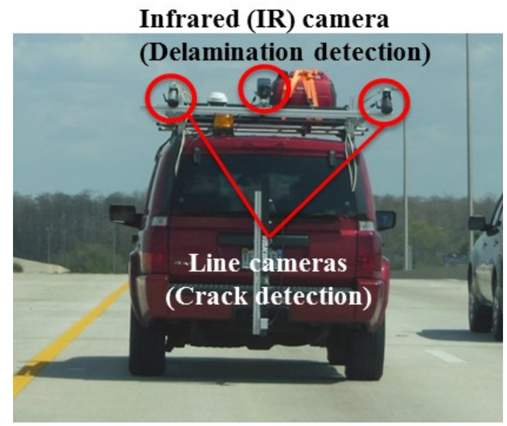
Scope: local level SHM using IRT & HD system

Infrared thermography (IRT) and High Definition (HD) image technology

IRT: subsurface defects (delamination, voids, etc.)

HD: surface defects (cracks, etc.)

- Non-contact
- Wide range of structures at one time
- High-speed scanning without lane closures



(SHRP2 Report: S2-R06A-PR-1)

Advantage of IRT & HD system: data collection, traffic control, safety, objectivity

Accuracy of IRT & HD

- HD: depends on image quality
- IRT: Some challenges & uncertainties

Focus on IRT

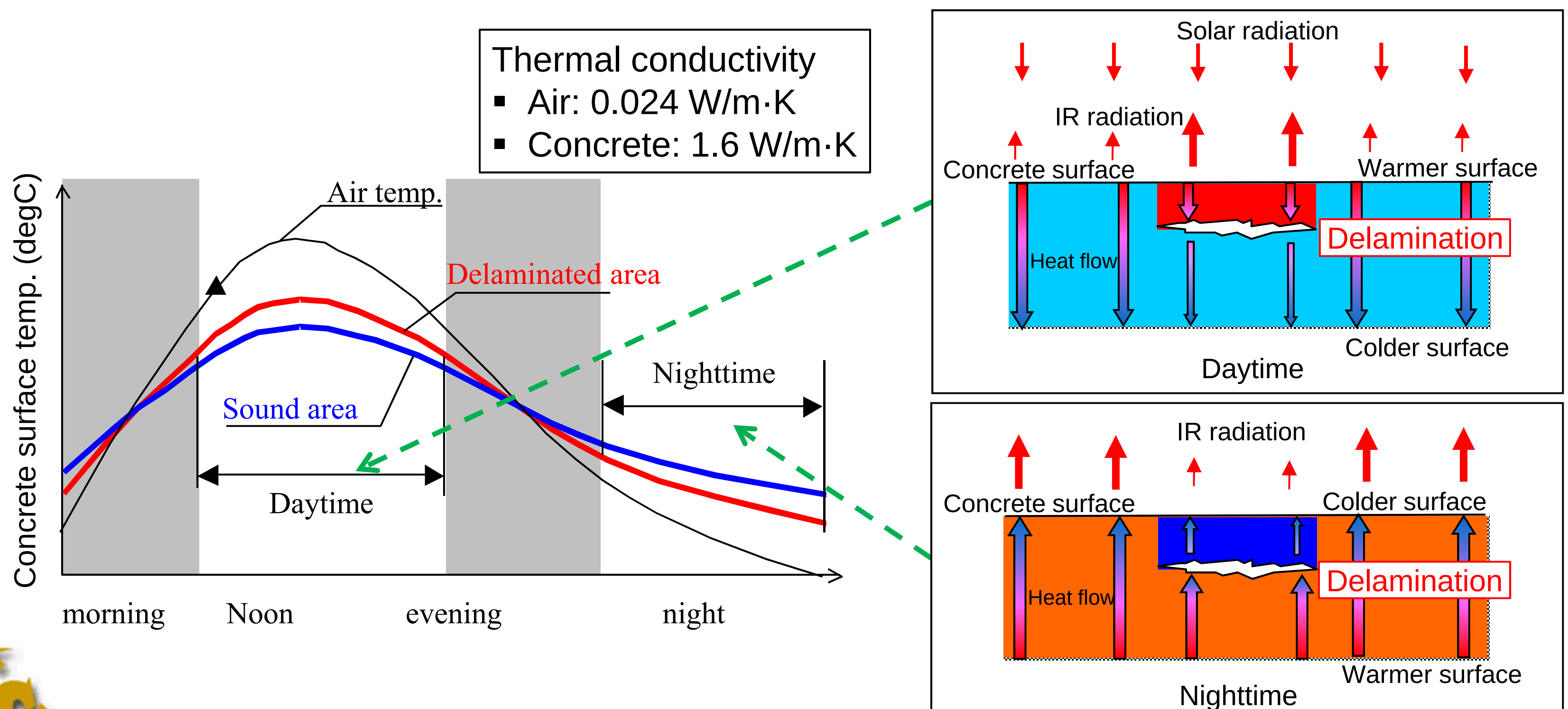
Principle of passive Infrared thermography (IRT)

- Solar radiation heats up the concrete surface
- Delamination (air) becomes a thermal insulator and prevents heat flow
- Causes temperature difference of concrete surface (ΔT)
- IRT detects subsurface defect from ΔT

  (IR cameras read the emitted IR radiation from the concrete surface and convert it to a temperature)

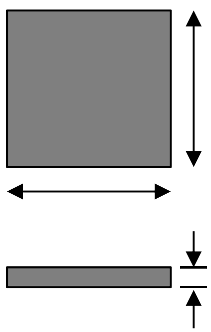
Thermal conductivity

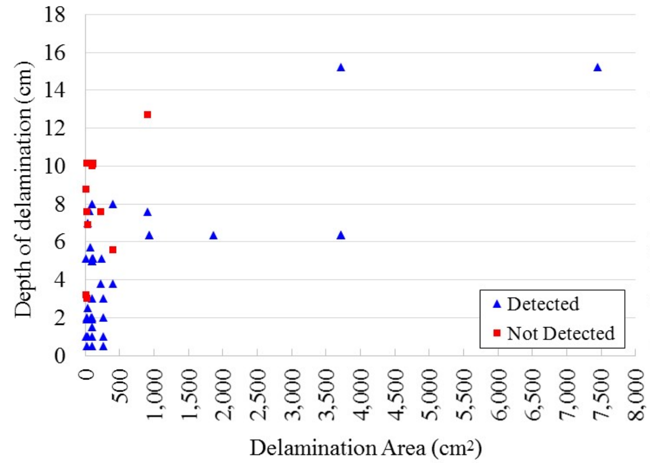
- Air: 0.024 W/m·K
- Concrete: 1.6 W/m·K

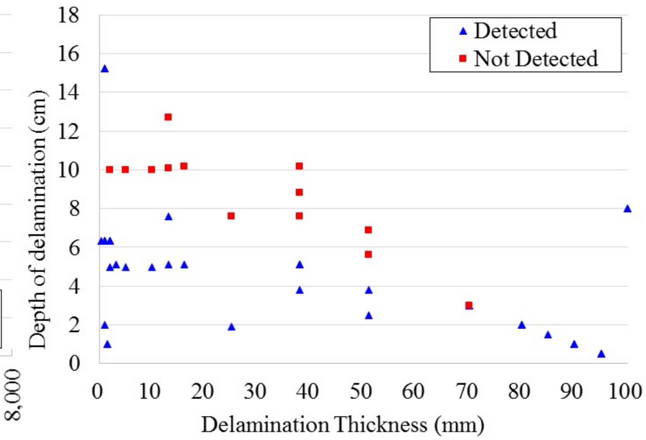


Challenges & uncertainties for IRT application

1) Delamination size

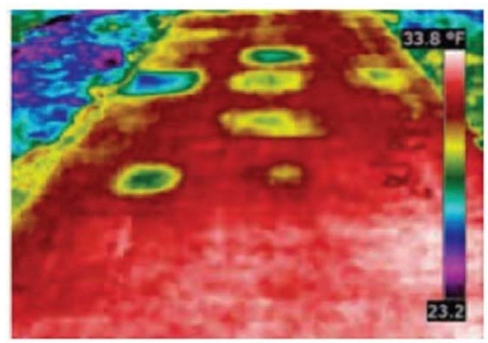




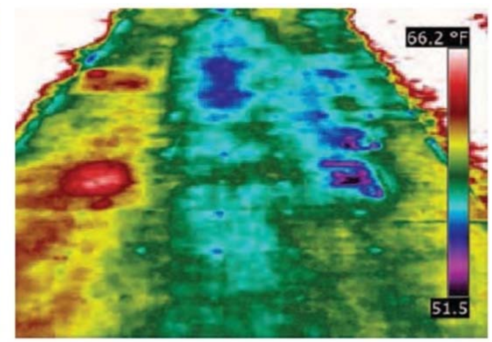


2) Data collection time

What time is good or bad?



40 min after sunrise



About noontime

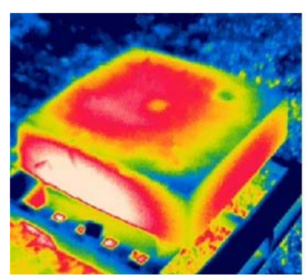
(SHRP2 Report: S2-R06A-PR-1)

3) Data collection speed & IR camera spec.

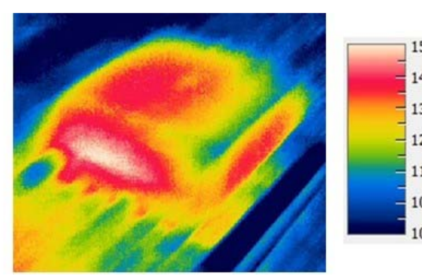
How data collection speed affects?

Camera spec?

(ASTM: ≤16km/h (10MPH))



0 km/h



48 km/h

Objectives of the study

- Reveal challenges & uncertainties for IRT
- Explore solutions, proper methods & ideal conditions
- Standardize Image-Based inspection

1. Effect of delamination size and its correlation to IRT
2. Suitable time window for IRT application
3. Effect of data collection speed & IR camera spec.
4. Evaluate the accuracy of high-speed scanning
5. How to utilize NDE data for bridge management

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Test method

Difficulties for preparing test specimens

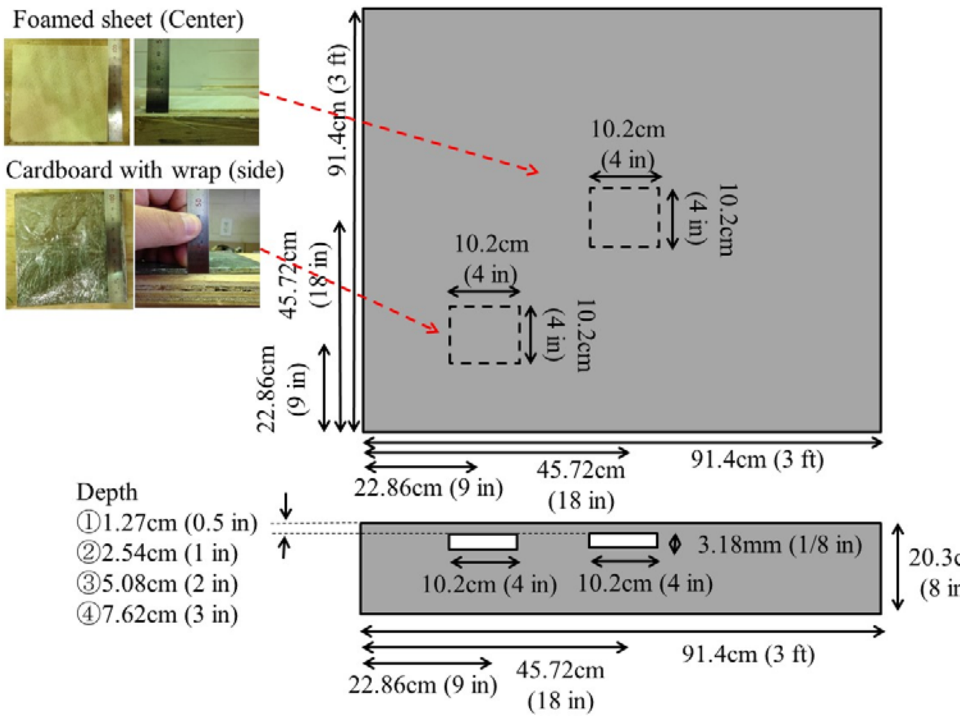
- Make several specimens and delamination
- Handle them under different conditions

⇒ *Limited test specimens have been utilized*

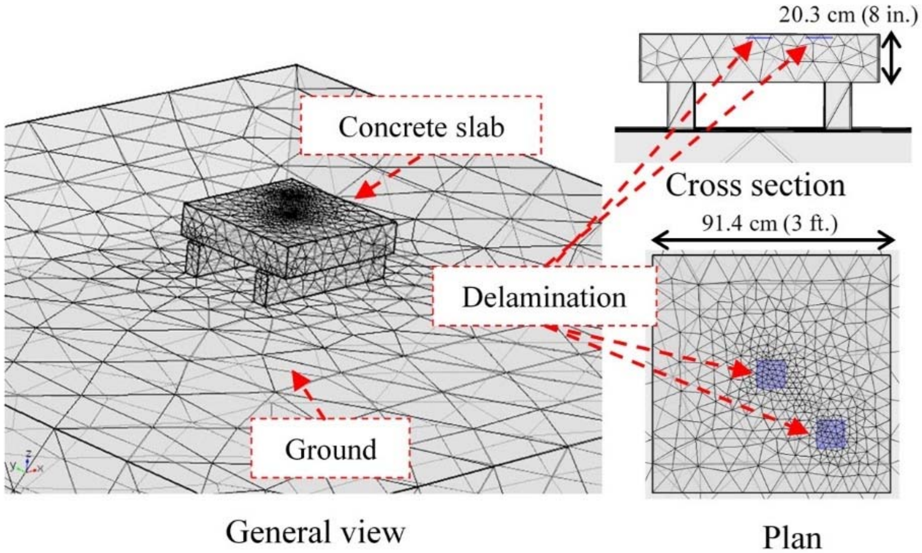
⇒ *IRT tests have been conducted under limited conditions*

Same size of FE model was developed (COMSOL Multiphysics)

(a) Test site situation



(b) Dimensions of test specimens



(c) FE model (same size of the concrete block)

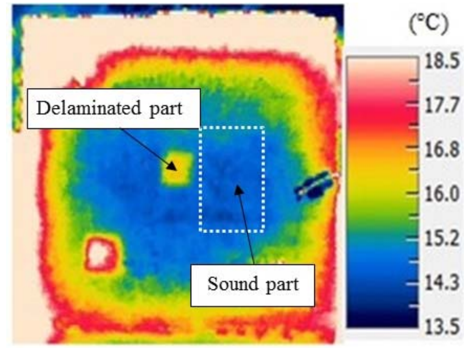
FE model validation

IRT data was collected;
- Every 30 minutes from 7 to 10 AM
- Every hour from 10 AM to midnight

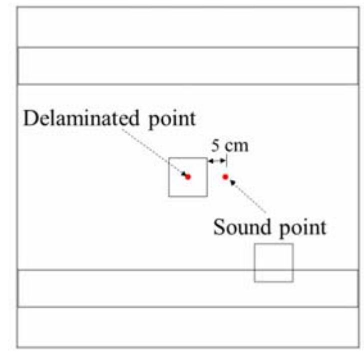
➡ Compared temperature differences b/w sound and delaminated parts

The disparities are less than 1 ºC
- ➢ Measurement error range
- ➢ IR cameras with different specifications indicated approx. 1 ºC at most

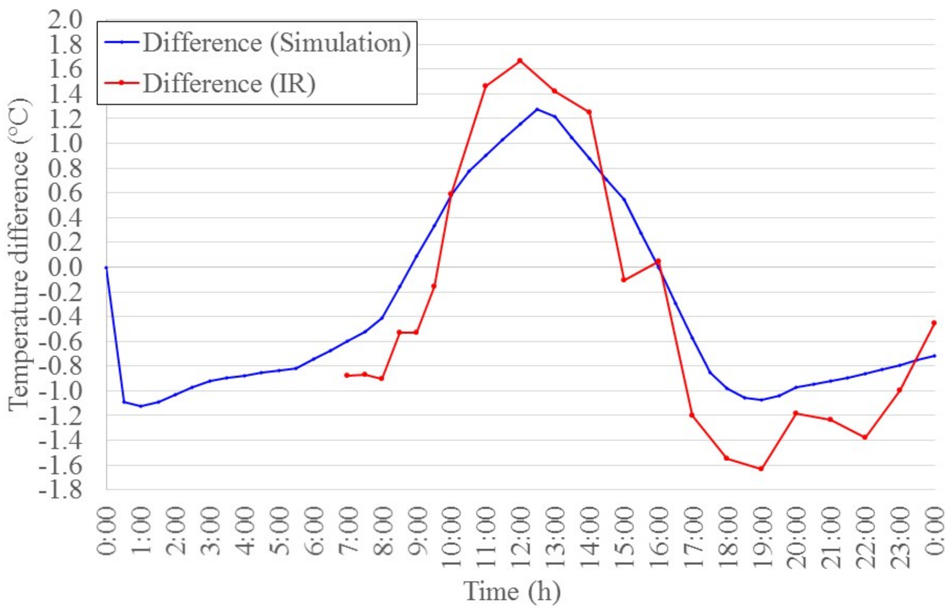
This FE model reproduced the temperature differences properly



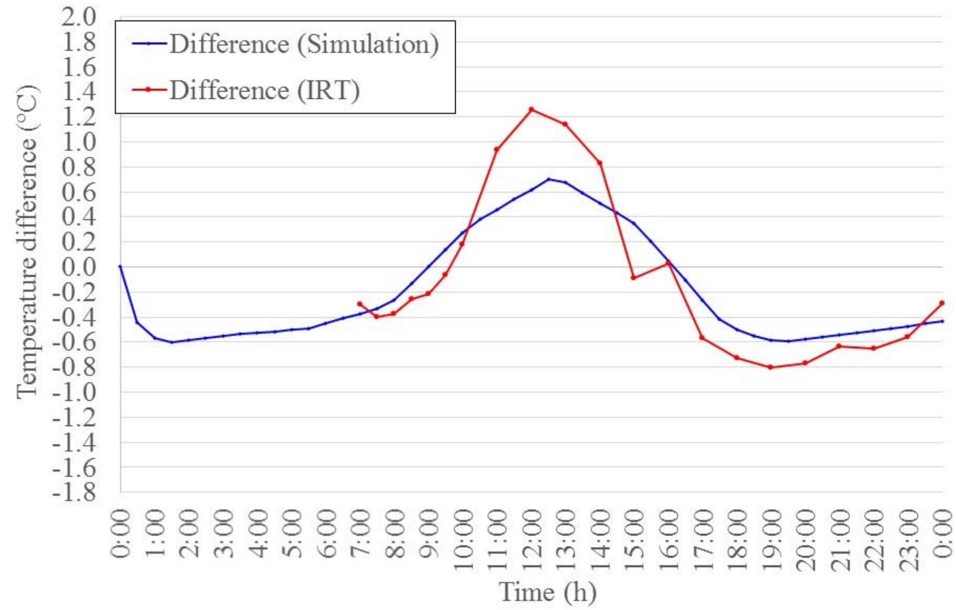
1.27 cm at 12 PM (noon)



Compared temperatures of delaminated and sound points

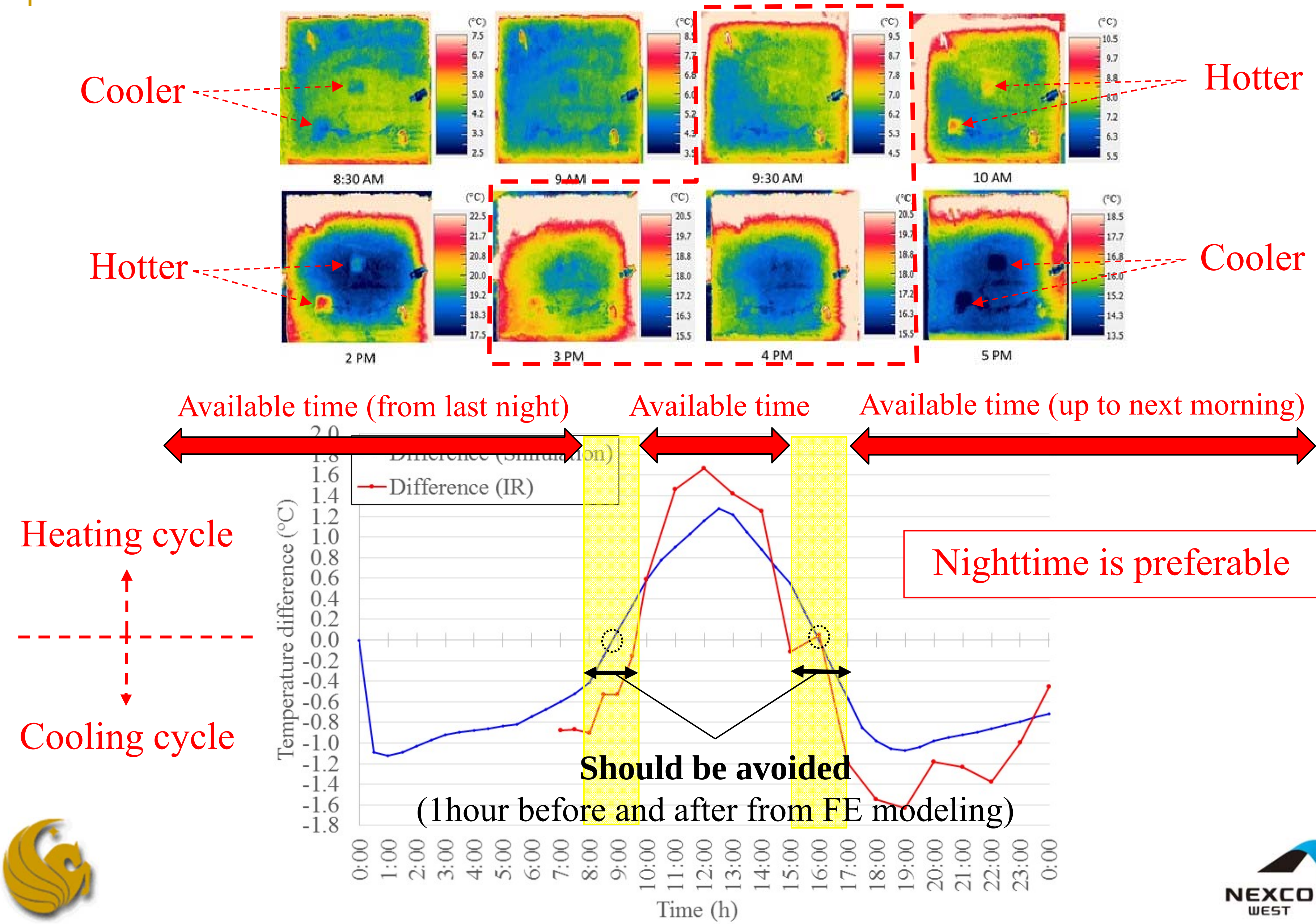


(a) 1.3 cm depth of delamination



(b) 2.5 cm depth of delamination

Suitable time window for IRT



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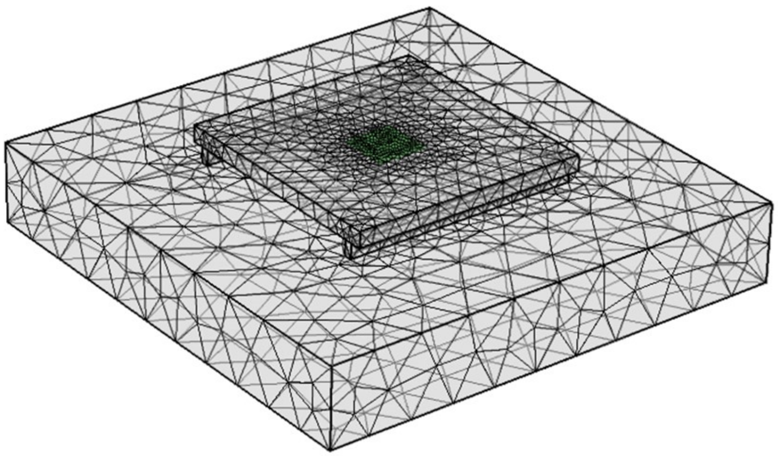
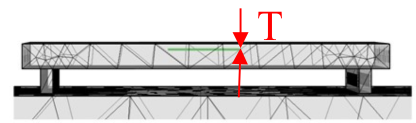
Effect of delamination size: FE model

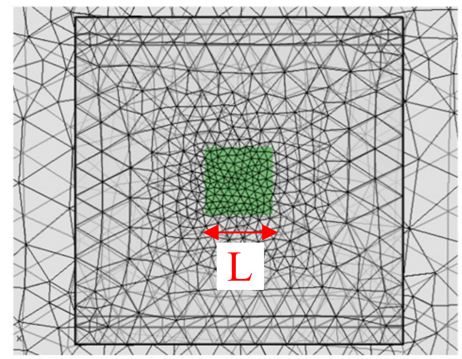
Same conditions of the FE model was used



(a) General view



(b) Cross section view



(c) Plan view

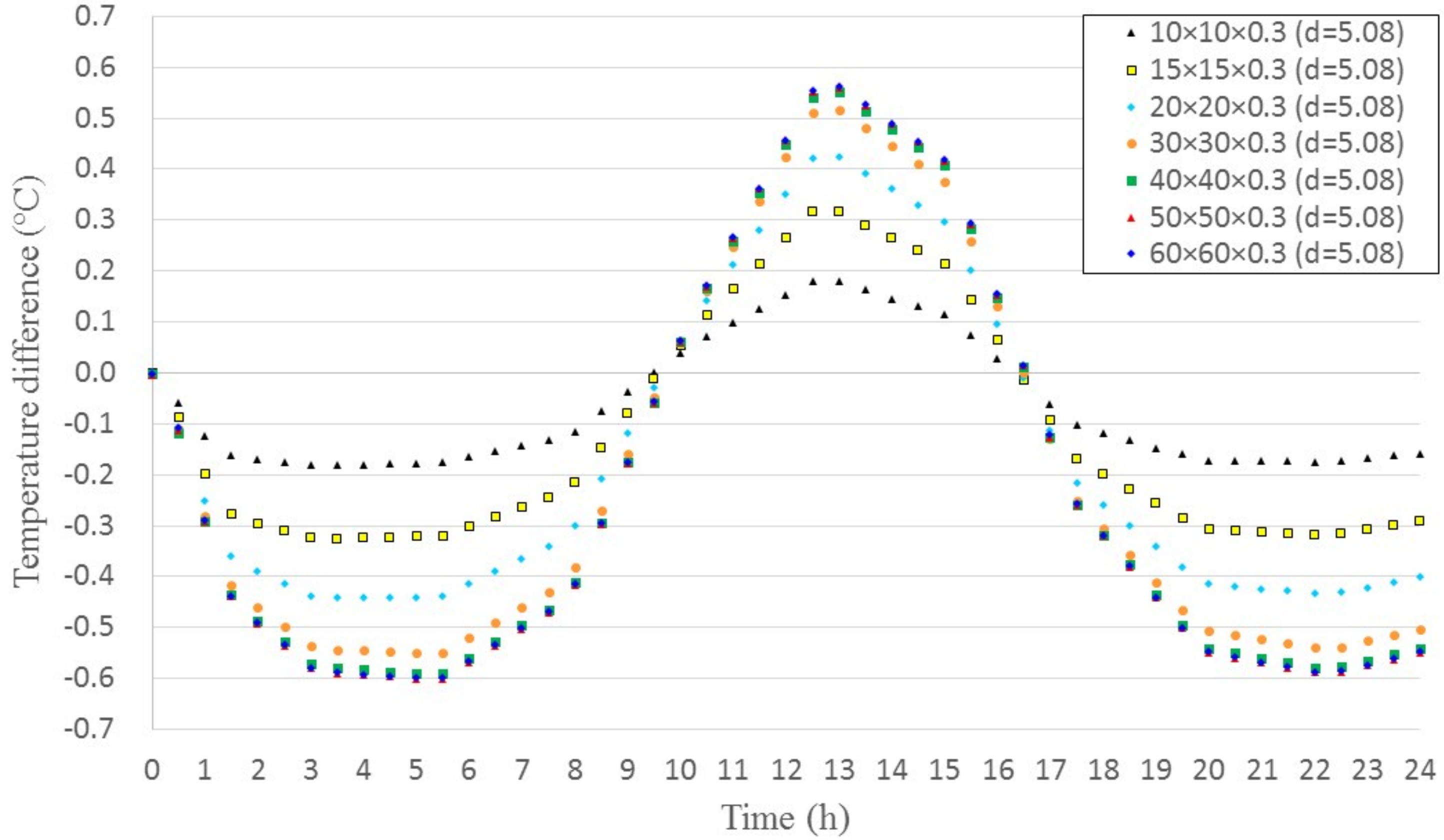
Dimensions of FE model:

- Concrete block: 300 × 300 × 20.3 cm (expanded)
- Delamination area: L = 10, 15, 20, 30, 40, 50 & 60 cm
- Delamination thickness: T = 0.1, 0.3, 1, 10, 15 cm
- Depth of delamination: 5.1 cm (2 in.) depth (typical top concrete cover)

Effect of delamination area

Simulated delamination at 5.1 cm depth:
A = 100 cm^2 to 3,600 cm^2, T = 0.3 cm, V = 10 cm^3 to 1,080 cm^3

- ΔT increases as the area increases
- ΔT converges to a certain value: approx. 40 × 40 cm



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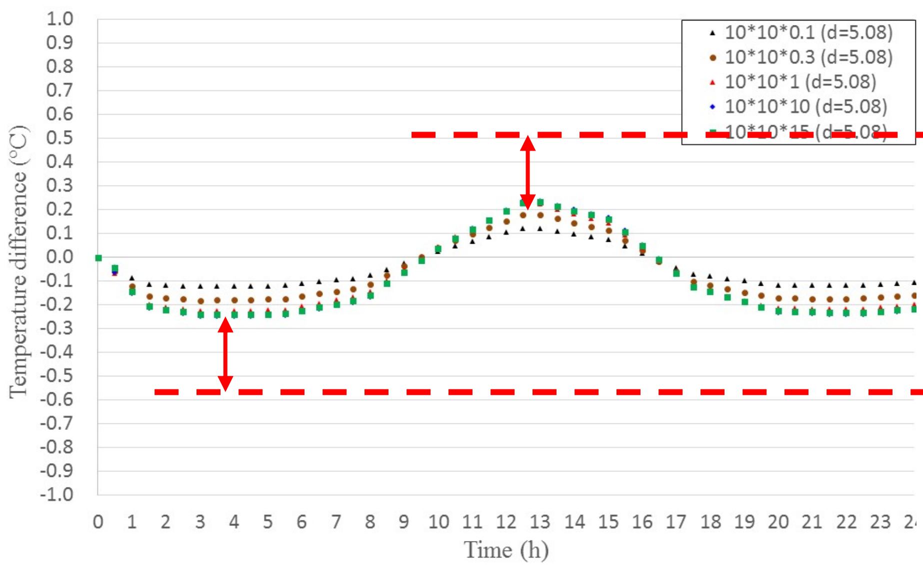
Effect of delamination thickness & volume

Simulated delamination at 5.1 cm depth:

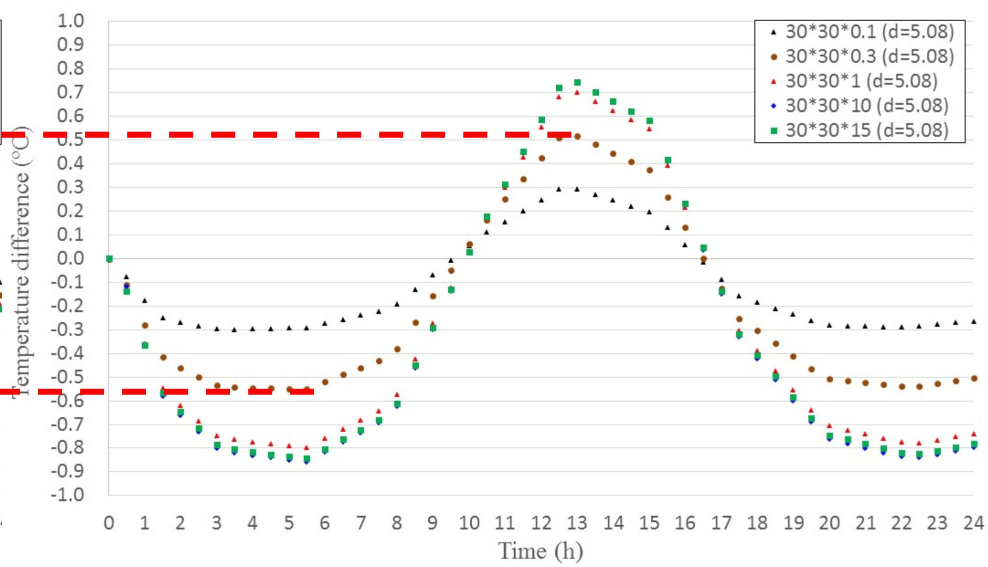
A = 100 cm^2 & 900 cm^2, T = 0.1 to 15 cm, V = 10 cm^3 to 13,500 cm^3

- A = 100 cm^2 :thickness and volume ⇒ insignificant impact on ΔT
- A = 900 cm^2 : ΔT increases as the thickness increases
- The effect of thickness increases as the area increases
- The effect of thickness converges to a certain value: approx. 1 cm
- Volume has no effect on ΔT

  (270 cm^3 (30 × 30 × 0.3 cm) >1,500 cm^3 (10 × 10 × 15 cm)



(a) 10 × 10 × T cm (5.1 cm depth)



(b) 30 × 30 × T cm (5.1 cm depth)

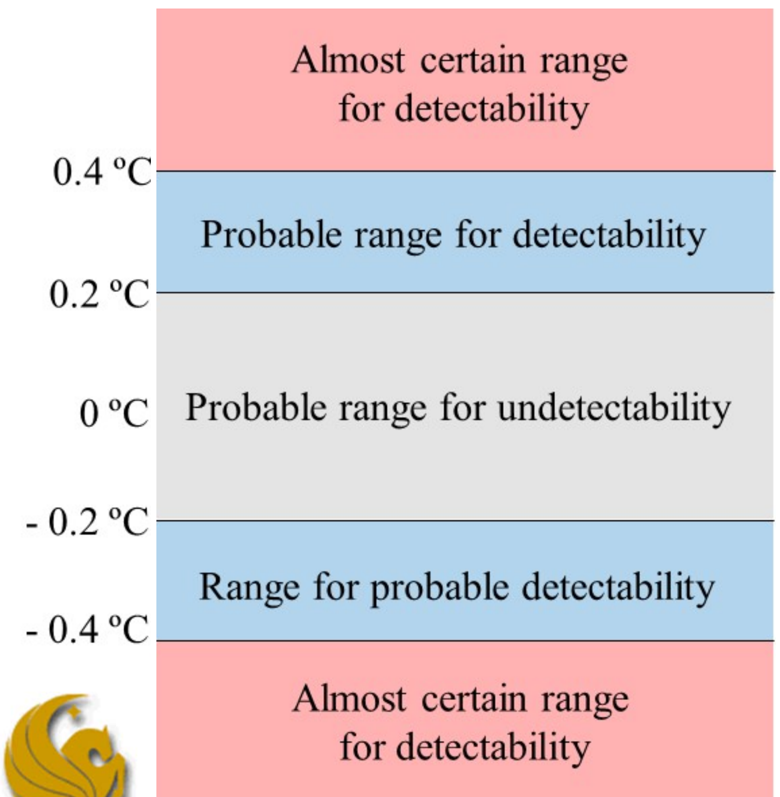
Detectable depth by IRT

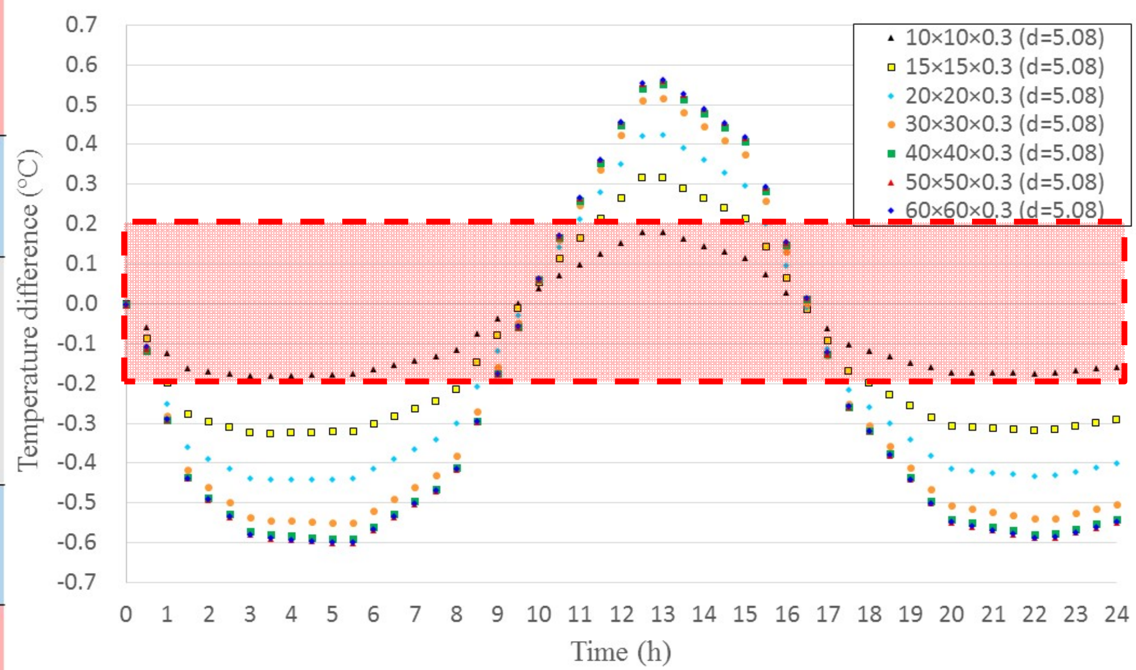
Assumed delamination detection range of ΔT

- Outside of ± 0.2 ºC: probably detectable by IRT

Delamination at 5.1 cm (2 in) depth

- If A ≥ 15 × 15 cm (T = 0.3 cm)





Field Laboratory Study

Explore factors which affect IRT for high-speed application

- ➢ Take IR images from a stopped and moving vehicle

IR cameras can be classified into two types:

- ➢ Thermal detectors (Uncooled cameras)
- ➢ Quantum detectors (Cooled cameras)

- Uncooled cameras: past studies
- Only one camera
  - ⇒ Economic reasons

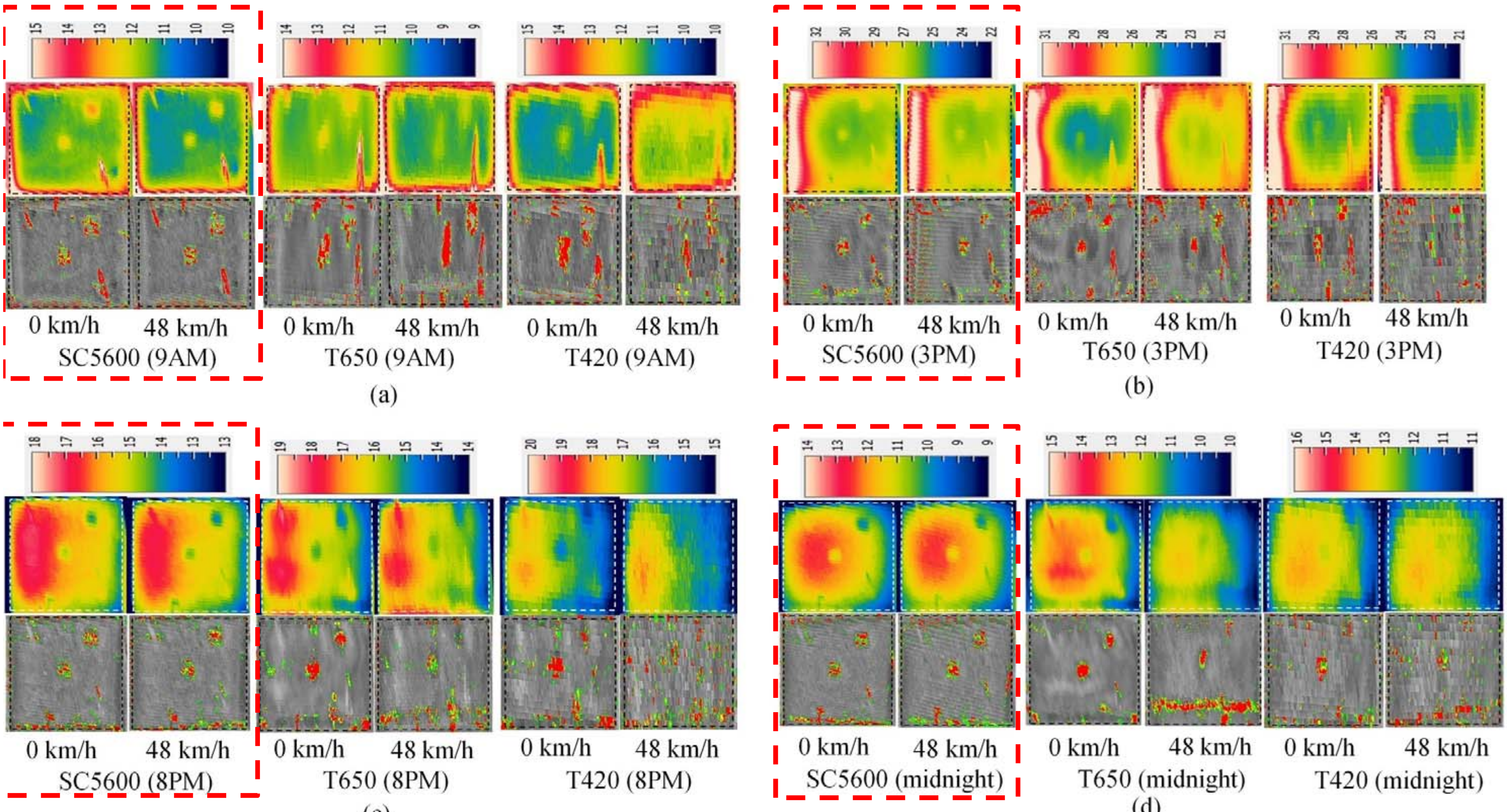
	Uncooled cameras			Cooled camera
Camera Number	**T420**	**T640**	**T650**	**SC5600**
Detector type	Uncooled microbolometer	Uncooled microbolometer	Uncooled microbolometer	InSb (Cooled)
Thermal Sensitivity (NETD)	<0.045°C at 30°C	<0.035°C	<0.02°C	<0.02°C at 25°C
Accuracy	±2° C or ±2%	±2° C or ±2%	±1° C or ±1%	±1° C or ±1%
Resolution	320 × 240 pixels	640 × 480 pixels	640 × 480 pixels	640 × 512 pixels
Spectral range	7.5 - 13 μm	7.5 to 14 μm	7.5 to 14 μm	2.5-5.1 μm
Field of View	25° × 19°	25° × 19°	25° × 19°	20° × 16°
Integration Time/Time Constant (Electronic Shutter Speed)	12 ms	8 ms	8 ms	10 μs to 20 ms

Test results

IRT data was collected;

- 9 AM, 3 PM, 8 PM and 12 AM (temp. range: 5K except 3PM (10K))
- At 0 km/h and 48 km/h

Only SC5600 was not affected



1.3 cm depth (0.5 in.)

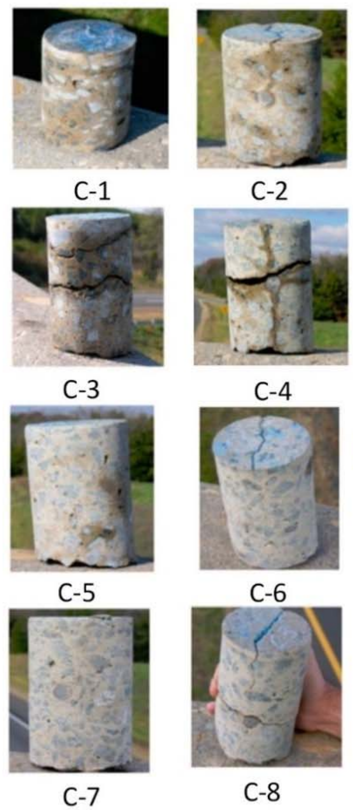
Comparative Study on a bridge

Comparison with other NDEs (Chain drag, IE, IRT, GPR)

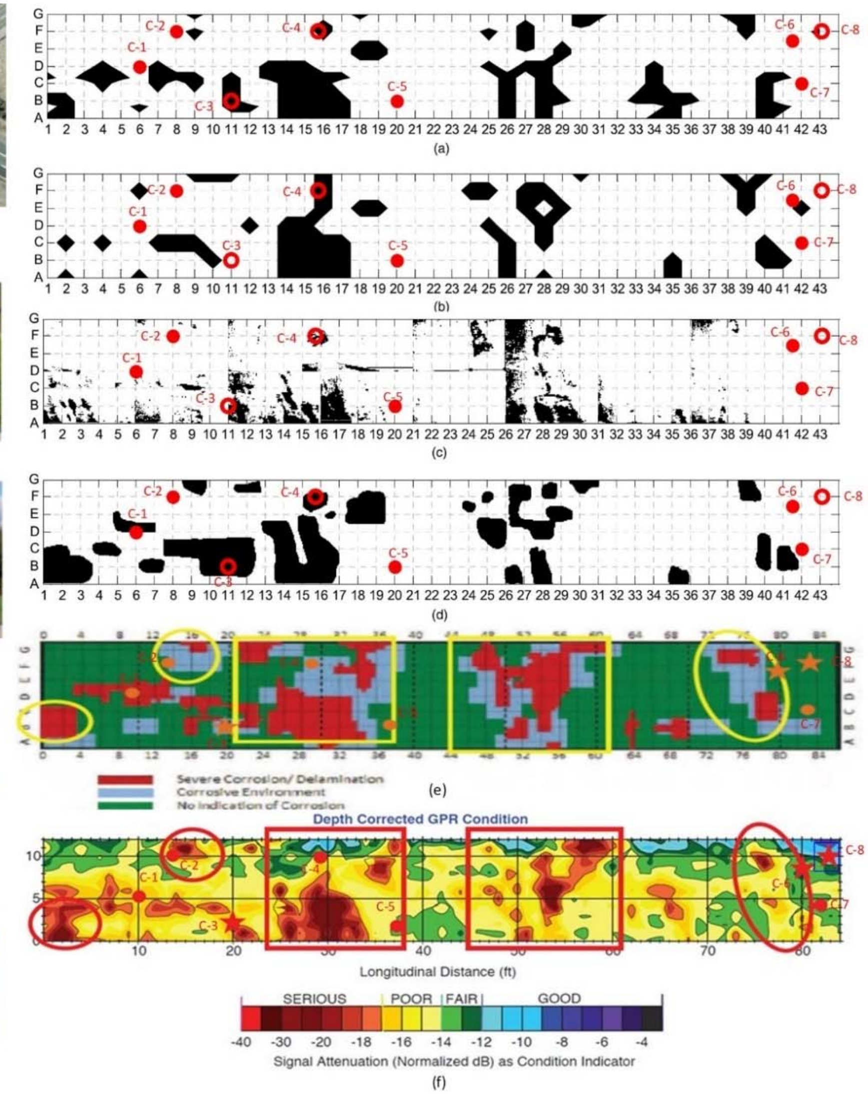
Bridge in Haymarket, VA

Camera setup

(1) Test location



(2) Core samples



(3) Test results: (a), (b) IE; (c) IRT; (d) Chain drag; (e), (f) GPR

(Empty circles indicate cores from delaminated areas)

(Source: Gucunski et al. 2013; Oh et al. 2013)

Comparison of core sample locations

Point	(a) IE - 1	(b) IE -2	(c) IR(T400)	(d) Chain drag	(e) GPR - 1	(f) GPR - 2	(1) IR(SC5600) (8:50 PM)	(2) IR(SC5600) (10:30 PM)	(3) IR(T640) (8:50 PM)	(4) IR(T640) (10:30 PM)	(5) IR(T420) (8:50 PM)	(6) IR(T420) (10:30 PM)	
C-1	○	○	○	× (FP)	× (FP)	○	○	○	× (FP)	× (FP)	× (FP)	× (FP)	sound
C-2	○	○	○	○	○	× (FP)	○	○	○	× (FP)	○	× (FP)	sound
C-3	○	× (FN)	○	○	○	○	○	○	○	○	○	○	delaminated
C-4	○	○	○	○	× (FN)	× (FN)	○	○	○	○	○	○	delaminated
C-5	○	○	○	○	○	○	○	○	× (FP)	× (FP)	× (FP)	× (FP)	sound
C-6	○	○	○	○	○	○	○	○	× (FP)	× (FP)	○	× (FP)	sound
C-7	○	○	N/A	○	○	○	○	○	○	○	○	○	sound
C-8	○	× (FN)	N/A	× (FN)	× (FN)	× (FN)	× (FN)	○	○	○	× (FN)	○	delaminated
Accuracy	100%	75%	100%	75%	63%	63%	88%	100%	63%	50%	63%	50%	
FP(%)	No error	0%	No error	50%	33%	33%	0%	No error	100%	100%	67%	100%	FP/all errors

Note: FP = False Positive (Judged sound part as delaminated part)
FN = False Negative (Failed to detect delamination)

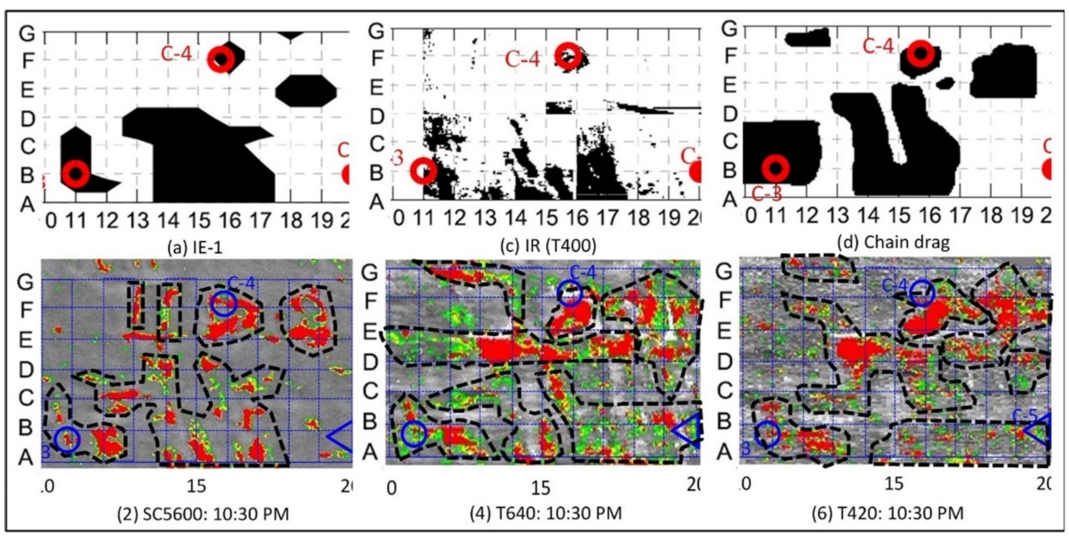
- Cooled camera (SC5600): most accurate (same as IE-1)
  (IRT: highway speed without lane closures; IE-1: w/ lane close)
- Uncooled cameras (T640 & T420): several False Positive misdetections
  ⇒ Less reliable for high-speed scanning

Comparison of shapes of indicated delamination

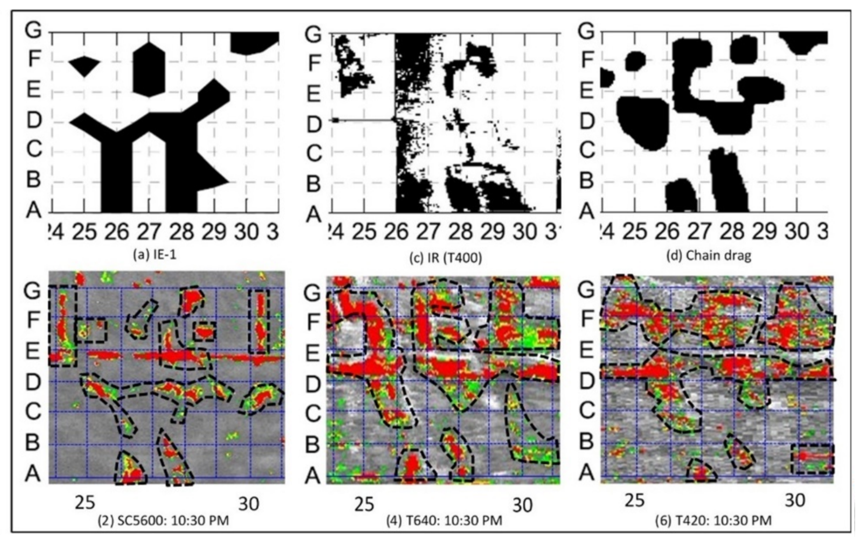
Compared with three NDE methods
(a) IE-1, (c) IRT (with T400), (d) Chain drag

- SC5600 shows identical indication with other NDE methods
- T640 & T420 show larger area of damage indications
- Uncooled cameras were affected by high-speed application

IRT with a cooled camera has a high potential to evaluate bridge deck condition accurately at highway speeds without lane closures



(a) 10 to 20 of Horizontal Test Coordinate



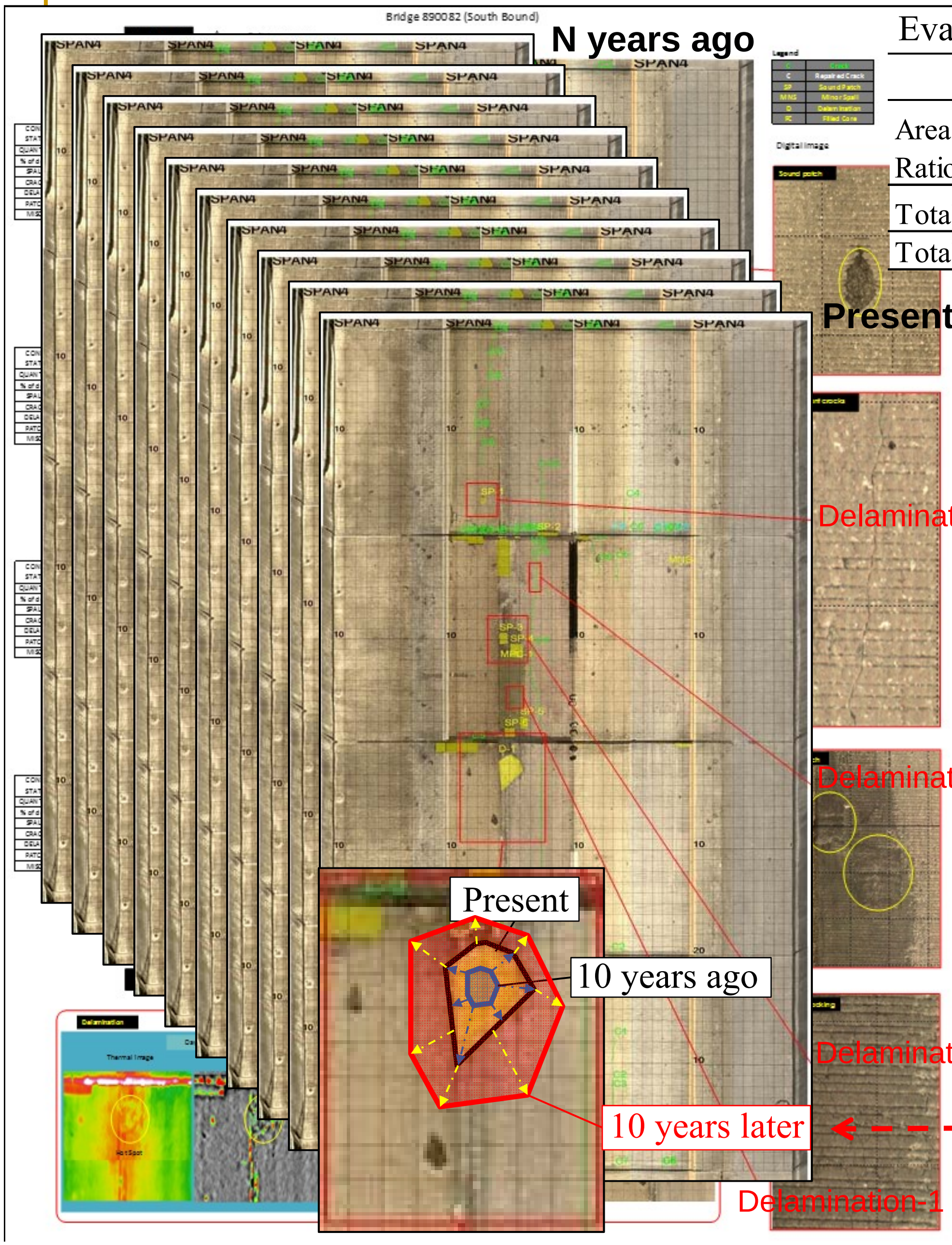
(b) 24 to 31 of Horizontal Test Coordinate

Conclusions for uncertainties of IRT

1. Effect of delamination size and its correlation to IRT
   - Area of delamination is the critical factor
   - Detectable depth: highly dependent on the size of delamination
2. Suitable time window for IRT application
   - Nighttime is preferable for bridge deck inspection
3. Effect of data collection speed & IR camera spec.
   - Slow shutter speed of uncooled cameras are affected
   - Cooled cameras has a high potential for high-speed scanning
4. Evaluate the accuracy of high-speed scanning
   - Cooled cameras: similar level or better accuracy than other NDEs

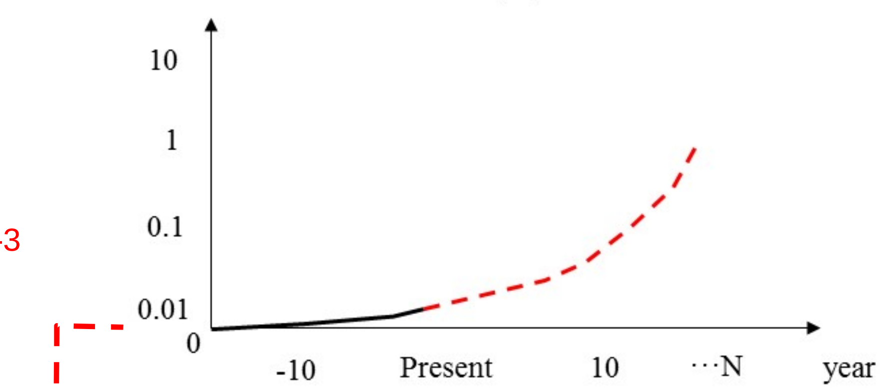
By understanding the limitations and capability of IRT, engineers can maximize the advantages for bridge inspections

Bridge management based on image-based inspection



Evaluation of bridge deck condition

Defect #	1	2	3	......	N
Area of defect (ft.^{2})	0.02	0.03	0.01	......	0.04
Ratio to the deck area (%)	0.01	0.01	0.01	......	0.01
Total defects area (ft.^{2})	0.1				
Total area ratio to the deck (%)	0.1				



Predict future defect grows ratio based on periodic inspection data

Recommendation for new inspection framework (Example)

If sever damage is detected

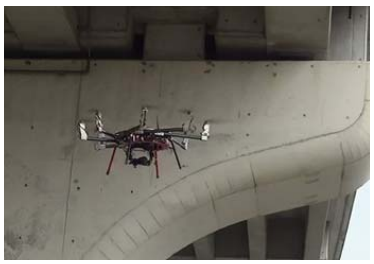
(IRT & HD)

Every year: High-speed scanning

- Bridge deck

w/ IRT & HD

Hundreds/Thousands times faster



(IRT & HD)

Every 2-3 years: Efficient inspection

- Superstructure, Substructure, Culvert, Railing, etc.

w/ IRT & HD

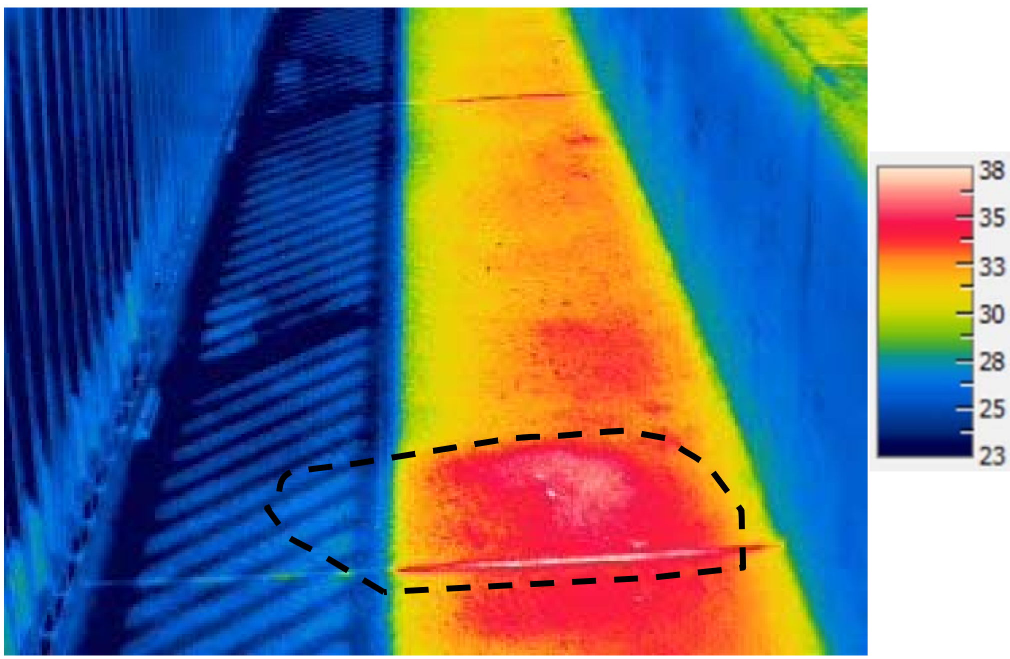
Every 5-6 years or as needed: Detailed inspection

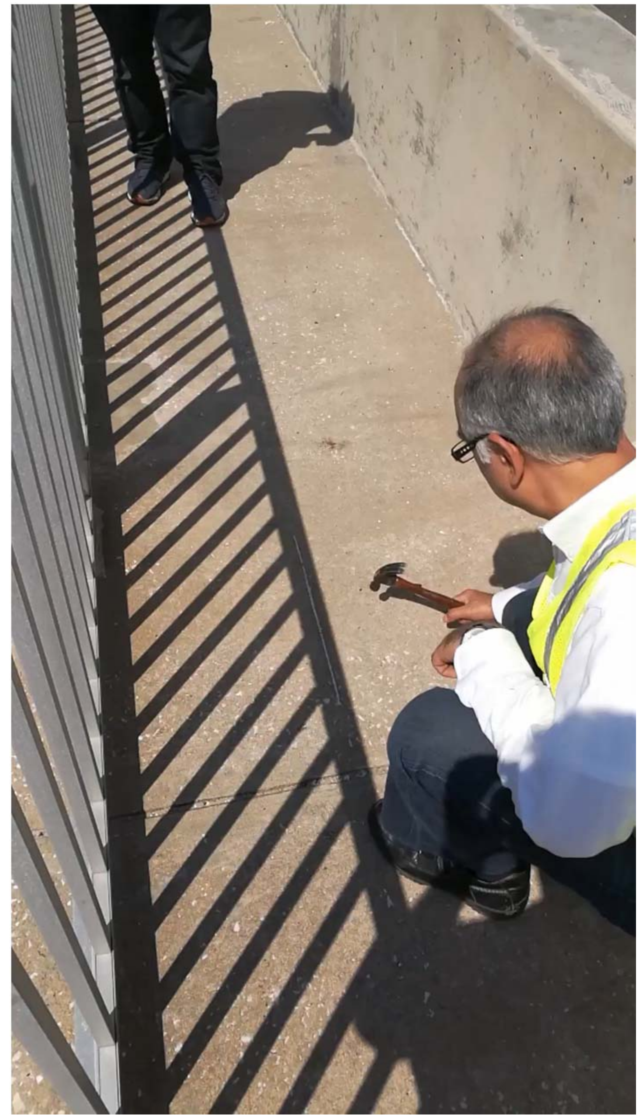
- Every component (including Bearing, Joint, etc.)
- Damaged parts detected above two inspections

w/ other NDE techniques (IE, GPR, Sounding, etc.)

Further Research need (Validation to prove the accuracy)

- Indicated area causes different sound
  ⇒ Validated
- Shaded part is difficult for IRT





Thank you for your attention!!

Any Questions?

【Contact Info】
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Effect of camera spec. for high-speed scanning

When T420 was used at 48 km/h

- IR image was blurred
- Damage indications became unclear

Shutter speed:

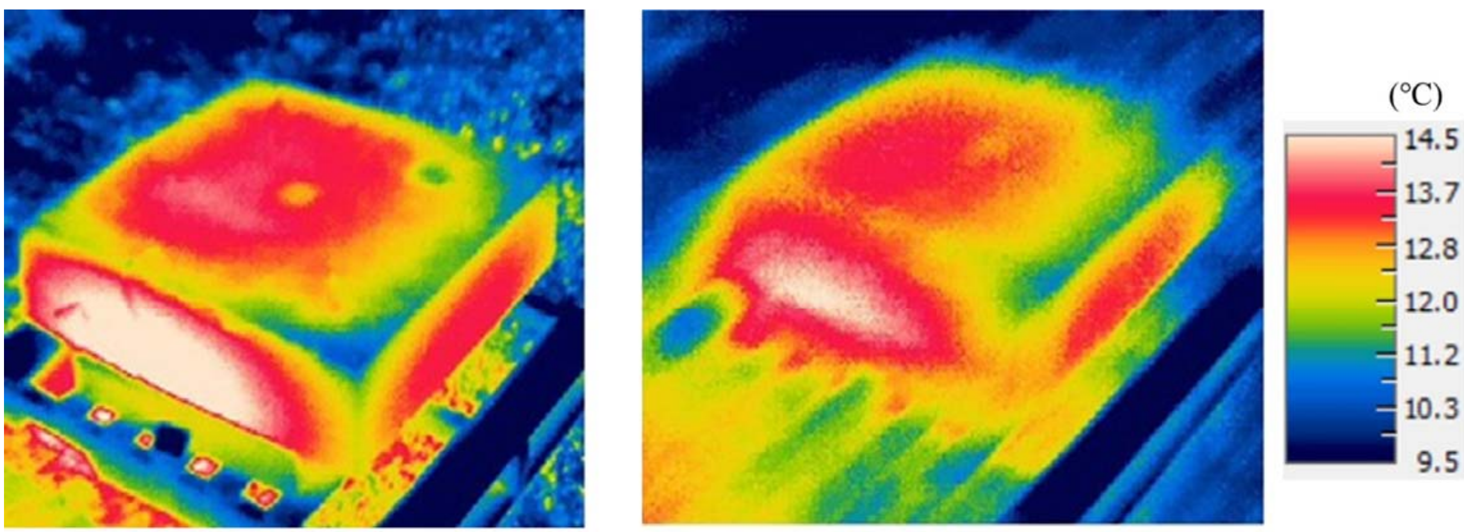
- SC5600: 3 ms (this experiment)
- T640: 8 ms
- T420: 12 ms

During one shutter

- T640 covers about 2.7 times
- T420 covers about 4 times

longer than SC5600

Uncooled cameras make blurred images due to slow shutter speed

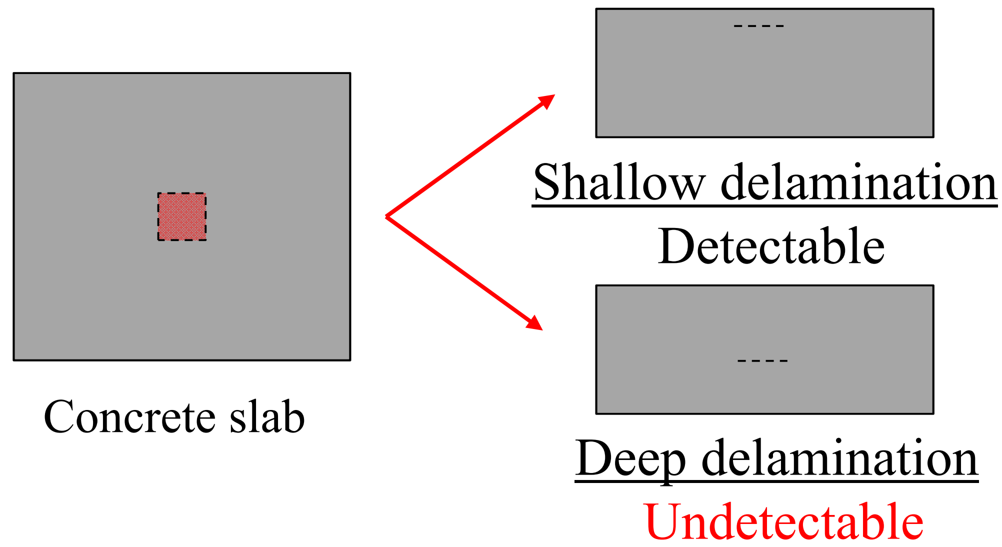


(a) Closer distance (0 km/h)   (b) Closer distance (48 km/h)

Delamination size and detectable depth

Detectable depth by IRT: highly dependent on the size of delamination

If area of delamination: small



If area of delamination: large