Bridge Deck Evaluation with Non-Destructive Testing

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I. INTRODUCTION

The aging and deterioration of highway bridges are inevitable with time.

→ Regular inspections and maintenance.

Because of numerous uncertainties in the field → difficult to detect.

→ Approximate approaches such as theoretical modeling and laboratory experiments are frequently employed

I. INTRODUCTION

More than 5.4% of bridges in Colorado, carrying 2.5 million vehicles a day, were rated structurally deficient as of 2020, and the state is under consistent pressure from an insufficient budget of $136 million per year.

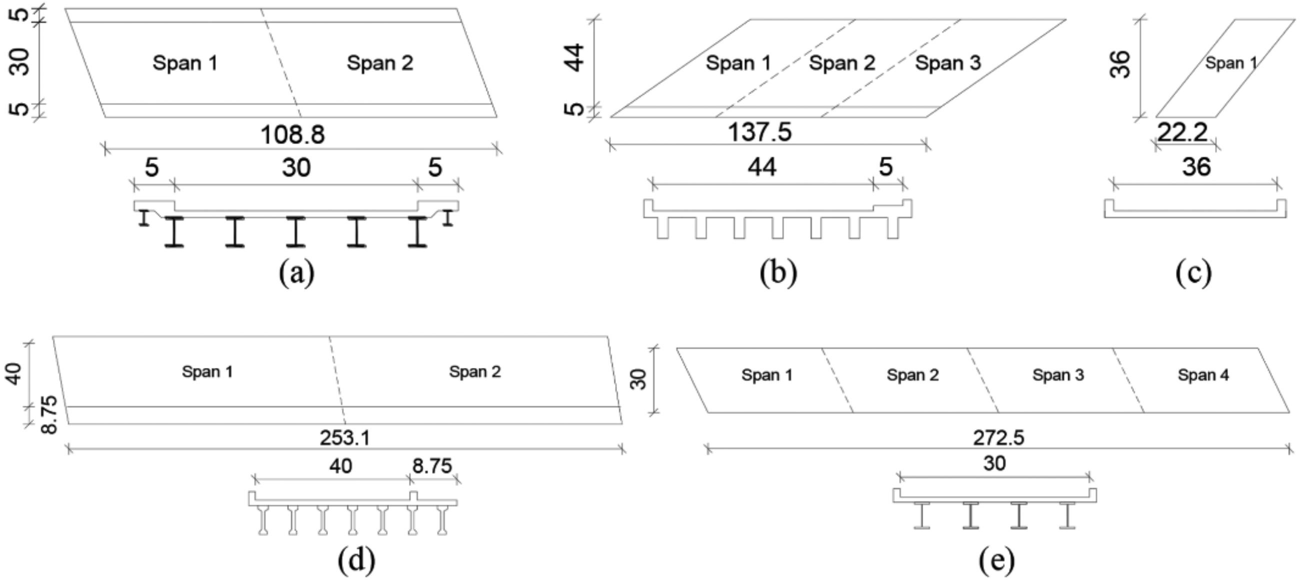
→ Diagnose the condition of bridge decks before the formation of major faults so that costly rehabilitation and replacement can be avoided.

→ Nondestructive testing such as Ground-penetrating radar (GPR) is an effective technique (the only available method).

I. INTRODUCTION

A rehabilitation project managed by the CDOT had a GPR-surveyed repair quantity of 4986 ft2 (463 m2) in a covered deck; however, after removing the asphalt layer, actual areas were found to be 414 ft2 (38 m2).

→ Study aims to propose a refined GPR interpretation approach.



(a) B06A; (b) B06S; (c) C08A; (d) B06V; and (e) C07A. (Note: Units in ft; 1 ft = 0.3048 m.)

Five benchmark reinforced concrete decks.

I. INTRODUCTION

Five benchmark reinforced concrete decks are singled out to investigate physical conditions through various nondestructive tests (rebound hammer, chain drag, and GPR) as well as through the National Bridge Inventory (NBI) records associated with visual inspections.

Analytical and computational models are formulated.

Nominal data of bridge structures.

ID	Year built	Number of spans	Length, ft	Width, ft	Skew, degrees	ADT	ADTT	Top steel reinforcing bar		Asphalt overlay
								Size	Spacing, in.	Thickness, in.
B06A	1952	2	108.8	30	30	5600	280	No. 5	12.75	4.0
B06S	1977	3	137.5	44	55	3000	330	No. 5	5.50	3.0
C08A	1954	1	22.2	36	40	5500	495	No. 4	9.00	6.0
B06V	1985	2	253.1	40	10	3200	192	No. 5	6.00	1.3
C07A	1967	4	272.5	30	30	5400	324	No. 5	10.00	3.3

Note: ID is identification; length is structural length; width is curb-to-curb width; ADT is average daily traffic; ADTT is average daily truck traffic; No. 4 = 0.5 in. diameter; No. 5 = 0.625 in. diameter; 1 ft = 0.3048 m; 1 in. = 25.4 mm.

II. NONDESTRUCTIVE TESTING

1. **Visual inspection.**
2. **Ground-penetrating radar.**
3. **Rebound hammer.**
4. **Chain drag.**

II. NONDESTRUCTIVE TESTING

1. Visual inspection.

A qualified inspector performed technical evaluations to rate the structural and geometric conditions of the five bridges.

II. NONDESTRUCTIVE TESTING

2. Ground-penetrating radar (ASTM D6087).

Electromagnetic waves were transmitted into the decks and reflections were recorded to quantify the severity of concrete degradation.

The signal attenuation and dielectric discontinuities of the reflected waves were interpreted to identify deteriorated regions.

II. NONDESTRUCTIVE TESTING

3. Rebound Hammer (ASTM C805).

Each traffic lane of the bridges was divided into three to four lines, and the strength of the deck concrete was recorded at intervals of 7 ft (2 m).

Because rebound readings are concerned with the hardness of an elastic material, degradation of the concrete cover (deck surface to top bars) was of interest.

II. NONDESTRUCTIVE TESTING

4. Chain drag (ASTM D4580).

An experienced field engineer dragged steel chains on the deck surface, compared tonal differences (clear vs. dull), and marked possible delaminated regions.

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III. TEST RESULTS

1. Visual inspection.

The evaluative information of the bridge decks excerpted from the NBI for the last decade (2010 to 2019). The deck condition rating was maintained to be 7 (Good condition: some minor problems); consequently, no major maintenance and rehabilitation were necessary.

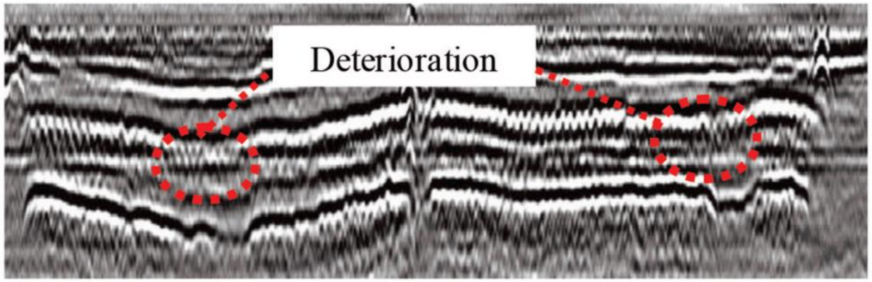
Information from NBI from 2010 to 2019

Identification	Deck condition	Deck geometry evaluation
B06A	7	3
B06S	7	9
C08A	7	4
B06V	7	6
C07A	7	4

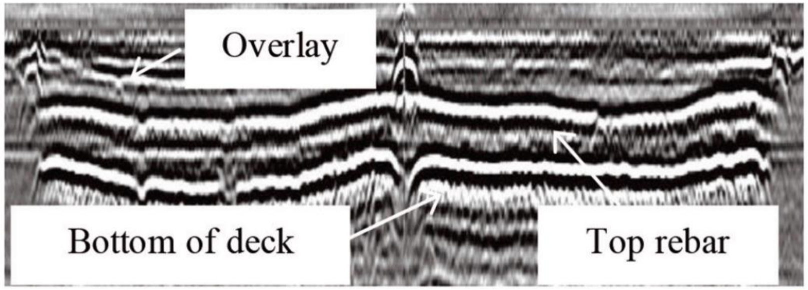
III. TEST RESULTS

2. Ground-penetrating radar.

The attenuated signals in the deteriorated regions, resulting from dissipated electromagnetic energy, signify the presence of chlorides, racking, and delamination in the deck concrete.



Electromagnetic waves were not able to penetrate the steel reinforcement, the top-bar location was conspicuous. Likewise, the interface between the asphalt and concrete was detected through their differences in dielectric contrast.



III. TEST RESULTS

2. Ground-penetrating radar.

Bridge ID	Total area*, ft²	Scan rate, scan/ft	Deterioration			Average reinforcing bar depth†, in.	Average overlay thickness†, in.	
			Area, ft²	Ratio, %	Average, %			
B06A	3264	4	414	12.7	12.6	5.2	2.0	(4.0)
		8	402	12.3				
		12	416	12.7				
		16	387	11.9				
		20	440	13.5				
B06S	6050	4	659	10.9	12.1	5.1	2.6	(3.0)
		8	847	14.0				
		12	773	12.8				
		16	672	11.1				
		20	719	11.9				
C08A	799	4	75	9.4	7.6	4.9	2.6	(6.0)
		8	57	7.1				
		12	55	6.9				
		16	70	8.8				
		20	45	5.6				
B06V	10,124	4	1311	12.9	12.7	4.5	1.7	(1.3)
		8	1174	11.6				
		12	1300	12.8				
		16	1243	12.3				
		20	1402	13.8				
C07A	8175	4	1698	20.8	21.4	4.1	2.0	(3.3)
		8	1874	22.9				
		12	1650	20.2				
		16	1818	22.2				
		20	1722	21.1				

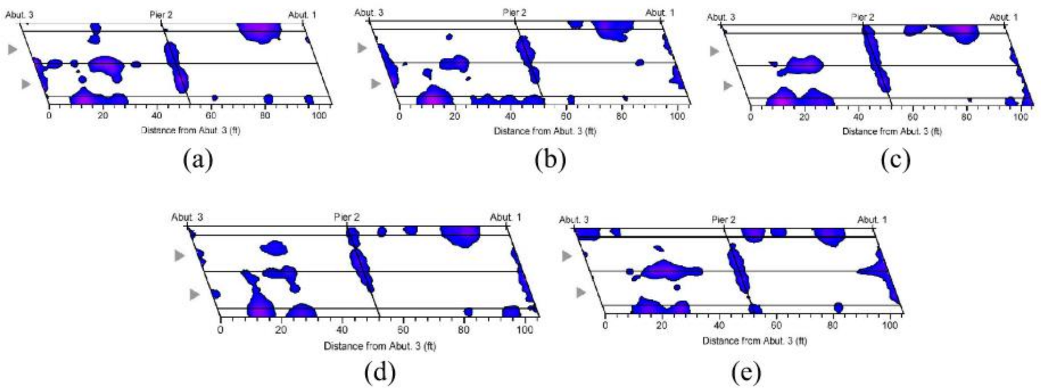
*Total area is structural length (NBI Item No. 49) multiplied by curb-to-curb width (NBI Item No. 51).

†Measured from deck surface.

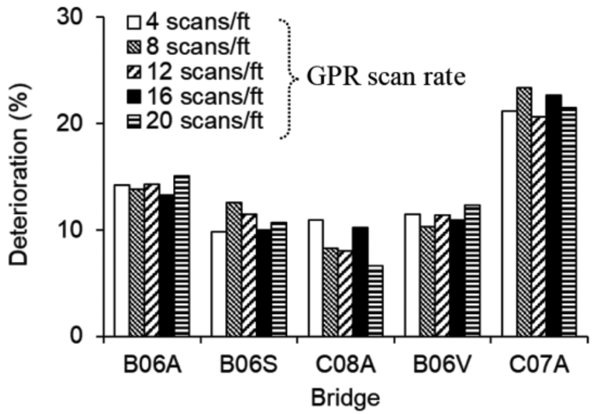
Note: 1 ft² = 0.0929 m².

2. Ground-penetrating radar.

GPR maps with variable scanning rates.



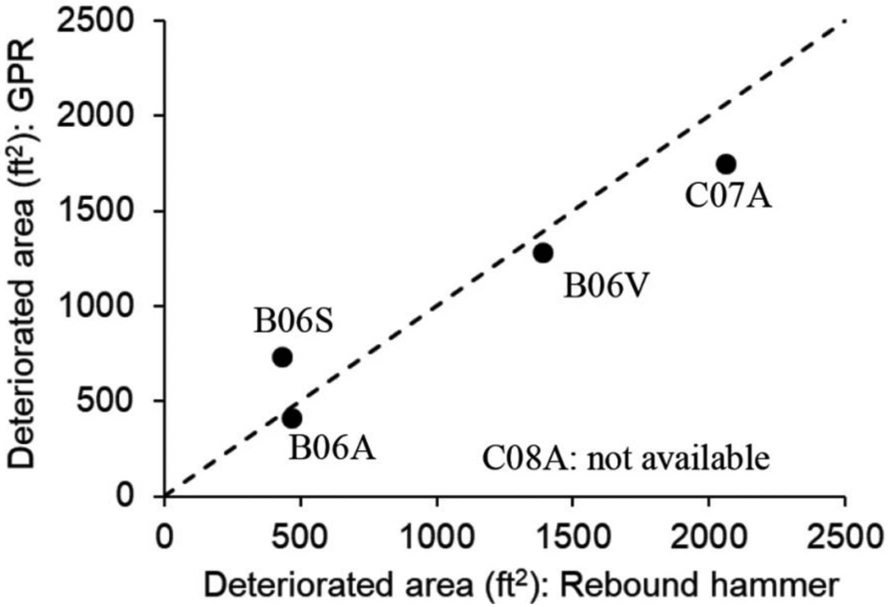
B06A: (a) 4 scans/ft; (b) 8 scans/ft; (c) 12 scans/ft; (d) 16 scans/ft; (e) 20 scans/ft



scanned data for deterioration

3. Rebound hammer.

A 20% reduction of the average strength was set as the limit. The percentage of the measured values below the threshold was then multiplied by the deck area of each bridge to estimate the quantity of deterioration.

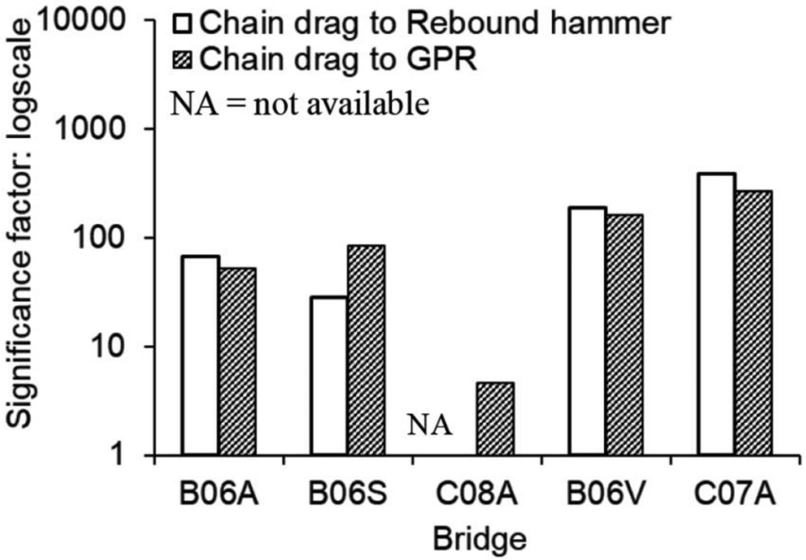


III. TEST RESULTS

4. Chain drag.

To demonstrate the extent of mutual agreement between the test methods, the significance factor (I) proposed by Barnes and Trottier was modified (I ≥ 5 means a noticeable discrepancy).

$$I = \frac{(A_A - A_B)^2}{A_{deck}}$$



III. TEST RESULTS

REPAIRED AREA SUMMARY

Bridge ID	Actual repair		Scan rate, scan/ft	GPR deterioration		Model-based delamination					
						Exact			Low bound		
	Area, ft^2	Ratio, %		Average area, ft^2	Ratio, %	Area, ft^2	Average, ft^2	Ratio, %	Area, ft^2	Average, ft^2	Ratio, %
B06A	0	0	4	412	12.6	18.44	9.15	0.28	26.96	13.03	0.39
			8			7.59			9.25		
			12			15.35			19.98		
			16			4.17			7.06		
			20			0.22			1.92		
B06S	20.9	0.35	4	734	12.1	0	0	0	7.67	7.85	0.13
			8			0			2.94		
			12			0			0.74		
			16			0			15.03		
			20			0			12.87		
C08A	0	0	4	60	7.5	14.77	3.21	0.40	17.59	4.34	0.54
			8			0			0.54		
			12			0			0.00		
			16			0			0.75		
			20			1.29			2.83		
B06V	7.6	0.08	4	1286	12.7	0	0.25	0.00	34.40	45.78	0.45
			8			0.89			49.11		
			12			0.34			44.13		
			16			0			31.44		
			20			0.03			69.80		
C07A	270.8	3.31	4	1752	21.4	161.46	99.12	1.21	161.46	99.12	1.21
			8			112.91			112.91		
			12			88.6			88.6		
			16			42.28			42.28		
			20			90.34			90.34		

Note: Ratio is ratio to total deck area; 1 ft^2 = 0.0929 m^2.

IV. ASSESSMENT OF DELAMINATION

1. Analytical modeling (El Maaddawy, T., and Soudki, K.).

The radial expansion of deck concrete due to reinforcing bar corrosion.

$$\delta = \frac{(1+\upsilon+\psi)(D+2\delta_0)}{2E_{eff}}P \qquad \psi = \frac{(D+2\delta_0)^2}{2C(C+D+2\delta_0)}$$

Where,

P is the radial pressure induced by the formation of corrosion rust

v is the Poisson's ratio of concrete (v = 0.2)

D is the diameter of the intact steel reinforcement

δ0 is the thickness of the porous zone between the concrete and reinforcement (δ0 = 0.0008 in. [20 μm], Thoft-Christensen)

C is the thickness of the hypothetical cylinder wall (C is clear cover of the reinforcing bar)

Eeff is the effective elastic modulus of the concrete

IV. ASSESSMENT OF DELAMINATION

1. Analytical modeling (El Maaddawy, T., and Soudki, K.).

The simplified uniform corrosion model, taken for modeling convenience, may be replaced by an alternative expression with localized corrosion.

$$t_i = \frac{(C/10)^2}{4D_{ce}}\left(\mathrm{erf}^{-1}\left(\frac{C_{cr}-C_0}{C_i-C_0}\right)\right)^{-2}$$

Dce is the diffusion coefficient in cm2/s (Dce = 3.1 × 10–9 in.2/s [2.0 × 10–8 cm2/s] for a typical deck

erf is the Gauss error function

Ccr and Ci are the critical and initial chloride concentrations (Ccr = 0.4% and Ci = 0% of the cement weight)

C0 is the equilibrium chloride (C0 = 1.6%)

IV. ASSESSMENT OF DELAMINATION

1. Analytical modeling (El Maaddawy, T., and Soudki, K.).

The concrete expansion at cracking (δcr)

$$\delta_{cr} = \frac{(1+\upsilon+\psi)(D+2\delta_0)Cf_r}{DE_{eff}} \qquad P_{cr} = \frac{2Cf_r}{D}$$

Pcr is the radial pressure at cracking

fr is the modulus of rupture

With the assumption that energy losses due to cracking are negligible and the corrosion products are uniform around the reinforcing bar, the rust-induced expansion can continue until the deck concrete delaminates at

$$\delta_{del} = \frac{f_r}{2}\left(\frac{S}{D}-1\right)\delta_{pp} \geq \delta_{cr} \qquad \delta_{pp} = \left(\frac{D(1+\phi(t))}{E(0)}\right)\left(1+\upsilon+D^2\left(\frac{2}{S^2}+\frac{1}{4C(C+D)}\right)\right)$$

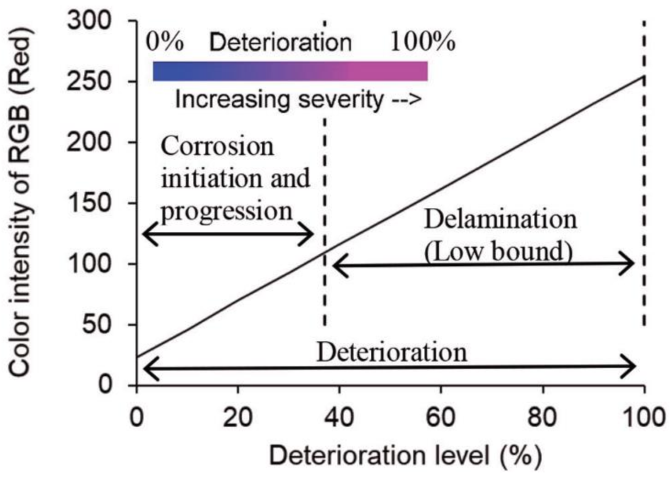
δdel is the concrete expansion at delamination; and S is the spacing of the reinforcing bars

IV. ASSESSMENT OF DELAMINATION

2. Agent-based modeling.

Preprocessing

The deterioration of the GPR contours was decoded in RGB model space, comprising a combination of red, green, and blue, so that the condition of the bridge decks was numerically linked with the scale bar.



After completing a calibration process, using the formulated analytical model.

IV. ASSESSMENT OF DELAMINATION

2. Agent-based modeling.

Implementation

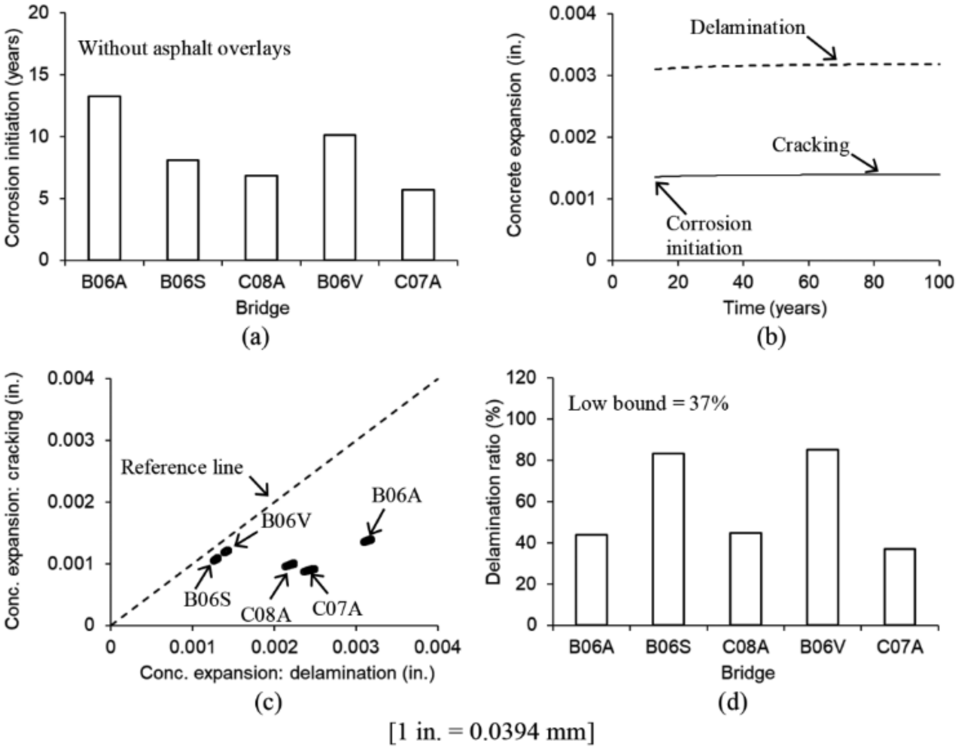
Calculate the delamination ratio

$$\lambda = \frac{\delta_{cr}}{\delta_{del}}$$

IV. ASSESSMENT OF DELAMINATION

3. Delamination of deck concrete.

Model-based delamination

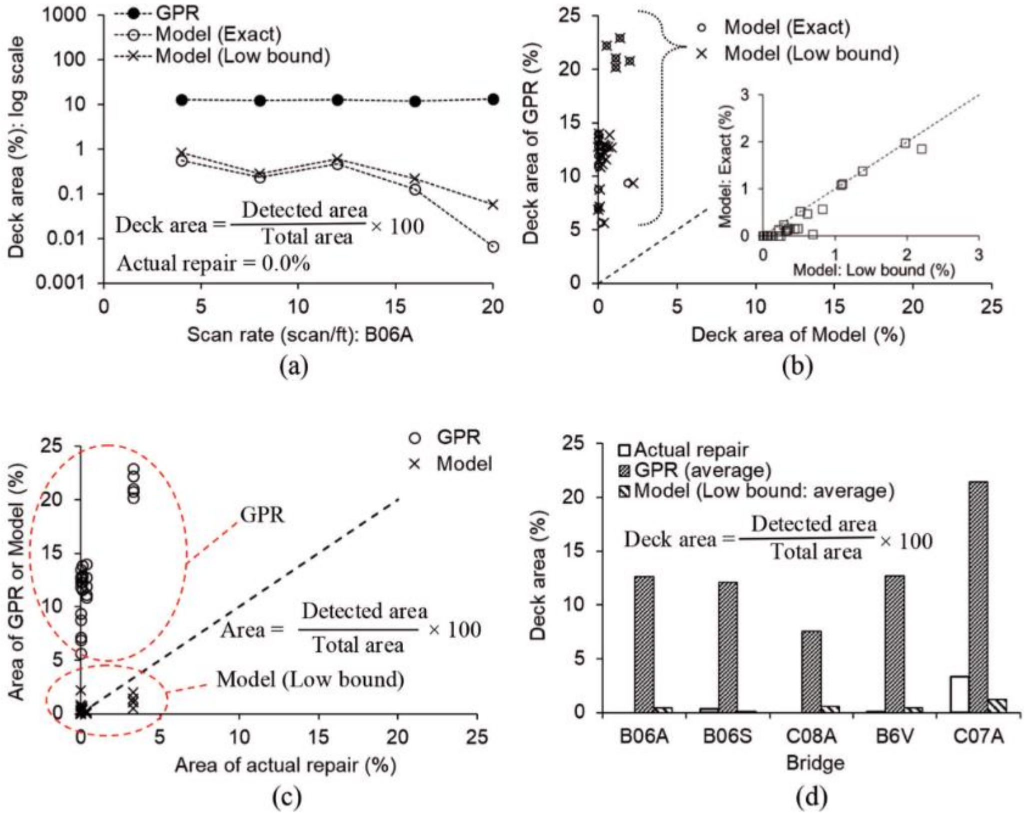


Corrosion-induced damage: (a) corrosion initiation time; (b) concrete expansion due to corrosion at cracking and delamination for B06A; (c) comparison among bridges; and (d) average delamination ratio (λ) for 100 years.

IV. ASSESSMENT OF DELAMINATION

3. Delamination of deck concrete.

Evaluation



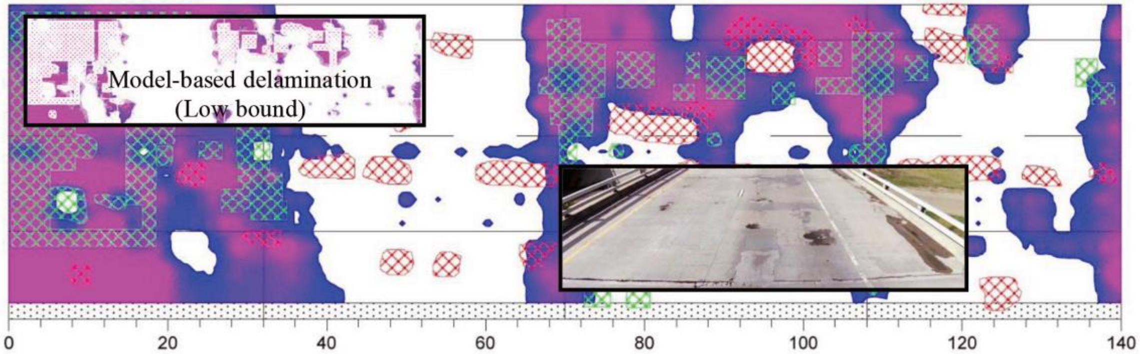
Evaluation of delaminated area: (a) deck area with scan rate for B06A; (b) comparison between GPR and model; (c) comparison among actual repair, GPR, and model; and (d) average comparison.

IV. ASSESSMENT OF DELAMINATION

3. Delamination of deck concrete.

Independent appraisal

The delamination ratio of λ = 40% was, then, applied to the GPR map of another bridge (F-20-BQ) on the interstate highway I-70.



The patch-repaired area was 1067 ft2 (99 m2). The area of deterioration (delamination) was quantified to be 2898 ft2 (269 m2) and 498 ft2 (46 m2) by GPR and infrared spectroscopy, respectively. In compliance with the proposed modeling approach, a delaminated area of 1022 ft2 (95 m2) was acquired at λ = 40%, which revealed an improved result against the repaired area.

V. CONCLUSION

The effectiveness of various nondestructive test methods has been investigated through five existing bridges in Colorado.

The GPR contour maps at variable scanning rates were employed to assess the extent of deterioration. Even though the scanning rates affected GPR readings, their statistical correlation was insignificant.

The low bound level of the model extracted delaminated areas using the deterioration intensity of the GPR scale above 40%, and reasonable agreement was made with the repaired areas.

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FOR PAYING YOUR ATTENTION!