NDE in Bridge Management Systems

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ABSTRACT

Methods for the use of NDE test data in bridge management systems are reported. NDE data are interpreted as condition ratings. Definitions of condition states are coordinated with thresholds for properties measured in tests. Data thresholds are the boundaries of condition states. Tests are directed at particular conditions and materials. Tests offer a determination of condition of elements relative to the focus of the test. Therefore, there are redundant, overlapping determinations of condition. Tests must be selected for the elements to be interrogated and for the expected types of deterioration. The tests considered here are standard tests for the evaluation of construction materials, and the examination of bridge elements in service. While standard data thresholds are available, these are adjusted to achieve a consistent assignment of condition states for all bridge elements and for all condition states.

TESTS AND CONDITIONS

Tests determine properties of bridge elements or materials. Tests indicate specific aspects of durability, deterioration or damage. Tests indicate specific types of deterioration. Test can be collected in four categories: Tests for protection of elements, tests for vulnerability, tests for attack, and tests for damage. Protected elements are resistant to aggressive agents. Protection is provided by features such as paint, sealers or membranes, and may be provided by superior durability of materials or design details. Elements are vulnerable when damage mechanisms such as corrosion or cracking can begin. Vulnerability is a lack of protection combined with environmental conditions that make the occurrence of a damage mechanism likely. Elements are attacked when a damage mechanism is active. Elements are damaged when there are detectable losses or cracks. Tests are collected in these categories in Table 1 through Table 4 for steel and reinforced concrete bridge elements.

Tests detect transitions among condition states. Four categories of tests detect four transitions, and therefore indicate five condition states. The five condition states are listed in Table 5.

These condition states are generic. Condition states are given explicit meaning for specific elements and types of deterioration. Examples are shown in Table 6.

New condition states for tests are similar to states for Commonly Recognized (CoRe) elements (*1*), and the states are compatible with element-level bridge management systems such as Pontis. There are differences, however, between CoRe condition states, and new states proposed for tests. New states all relate distinct conditions. CoRe condition states to a limited extent and NBI condition states to a larger degree define condition in terms of extent of deterioration. Where this is done, two condition states report the same

Table 1: Element Protection and Related Tests

Aggressive Agent or Condition	Protection	Assessment of Protection
RC, P/S Elements		
Deicing salts, other contaminants	Membrane on concrete	Ultrasound transmission time.
	Concrete sealer	Air permeability. Water permeability. Surface electrical resistance.
	Concrete permeability	AASHTO T277, AASHTO T259 and the other concrete permeability tests.
	Concrete quality	Ultrasound transmission velocity.
	Concrete cover of reinforcing steel	Magnetic cover meter.
	Epoxy coated rebars	Construction spec., AC resistance, coring.
	Galvanized rebars	Construction spec., coring.
	Grout around prestressing tendons	Construction spec., impact-echo.
	Grease around prestressing tendons	Construction spec + age.
ASR	Concrete mix design	Construction spec., material acceptance tests.
Freeze-thaw	Concrete mix design	Construction spec., material acceptance tests.
Steel Elements		
Exposure to atmosphere	Paint	Film thickness. Film adhesion.
	Surface coating (weathering steel)	Oxide adhesion and color.
Stress cycles	Low stress cycles, Design details	Comparison of stress cycle magnitude and number to fatigue limit.

Table 2: Element Vulnerability and Related Tests

Aggressive Agent or Condition	Vulnerability	Assessment of Vulnerability
RC & P/S Elements		
Deicing salts, other contaminants	Contaminant concentration	Sampling and assaying. Titration. Specific ion probe.
	Corrosion of rebar	Contaminant concentration at level of steel.
	Corrosion of prestressing tendon	Contaminant concentration in grout at tendon.
Exposure to atmosphere	Exposed rebar	Visual inspection.
	Exposed prestressing tendon	Visual inspection.
Steel Elements		
Exposure to atmosphere	Steel corrosion	Coating brittleness or lack of adhesion. Exposed steel. Surface staining.
	Surface coating (weathering steel)	Darkened, discolored oxide coating.
Stress cycles	Fatigue exhaustion and cracking	Comparison of stress cycle magnitude and number to fatigue endurance and age.

Table 3: Element Attack and Related Tests

Element / Part	Attack	Assessment of Vulnerability
	RC & P/S Elements	
Rebar	Corrosion	Half-cell potential. Corrosion current. Visual inspection
Prestressing tendon	Corrosion	Visual examination
	Wire breakage	Acoustic emission
	Steel Elements	
Steel	Corrosion	Visual inspection
	Fatigue cracking.	Acoustic emission.

type of deterioration. New condition states recognize properties in elements, notably protection, that are related to expected durability of elements. Newly constructed elements may begin life in state 2, *Exposed*, if material quality is not adequate or protection is absent. This differs from other sets of condition states, including CoRe states, in which new elements are always in state 1. New condition states *Protected*, *Exposed*, and *Vulnerable* all address conditions that may not be visible, or at least not visible for all types of elements. Older sets of condition states are adapted primarily to visual inspection, and so report damage, but not vulnerability or exposure of elements (*2*).

CONDITION RATING USING TEST DATA

Condition ratings are the findings of tests reported in a form that is compatible with bridge management systems. To make this report, test data are interpreted. For many tests, interpretation is binary. Test data are compared to a threshold value. Each threshold is the boundary between two condition states for a measurable property. Just like the specific definitions of condition states (Table 6), tests address specific materials, specific deterioration, and particular pairs of condition states.

There are separate tests for each of the four transitions among five condition states. These may be noted as

Table 4: Element Damage and Related Tests

Damage Mechanism	Damage	Assessment of Damage
	RC & P/S Elements	
Corrosion of reinforcing steel	Spalls, Delaminations, Cracks	Visual inspection, sounding, radar, infrared thermography, ultrasound.
	Steel losses	Visual inspection. Corrosion current + time.
	Broken prestressing wires	Visual inspection. Magnetic flux inspection.
	Steel Elements	
Corrosion	Loss of section	Visual inspection. Ultrasonic thickness meter. Other thickness measurements.
Crack growth	Cracking	Acoustic emission. Ultrasound crack detection and measurement. Magnetic particle flux. Dye penetrant. Eddy current. Radiography.

Table 5: Condition States for Tests

Protected	-	Aggressive agents can not enter or accumulate.
Exposed	-	Aggressive agents can enter or accumulate.
Vulnerable	-	Aggressive agents exist at such level that a damage mechanism may begin.
Attacked	-	Damage mechanism is active.
Damaged	-	There is damage such as section loss, cracks, delaminations, spalls, etc.

$Test_{Pro}$ - Tests for protection system, for material resistance, or for material durability.

$Test_{Vul}$ - Tests for contamination, or for conditions that promote damage mechanisms.

$Test_{Att}$ - Test for activity of damage mechanisms.

$Test_{Dmg}$ - Test for detection and measurement of damage.

While tests are the focus here, the concept of organization of observations by any means along a condition state scale can be followed. As an example, the tests and observations named in the AASHTO manual of condition assessment (*6*) are coordinated with condition states in Table 7 and Table 8.

The determination of conditions then is the collection of test data, interpretation of data, and assignment of condition ratings. For *Protected* and *Exposed* condition states, the process is written as

$$If(x_{Pro} < T_{Pro})\,then\ Protected$$
$$If(x_{Pro} \geq T_{Pro})\,then\ Exposed \qquad \text{(Eq. 1)}$$

where x_{Pro} are data from a test for the *Protected* condition state and T_{Pro} is the threshold for the protected condition state. For *Exposed* and *Vulnerable* condition states,

$$If(x_{Vul} < T_{Vul})\,then\ Exposed$$
$$If(x_{Vul} \geq T_{Vul})\,then\ Vulnerable \qquad \text{(Eq. 2)}$$

Table 6: Examples of Condition States

Condition States				
Protected	Exposed	Vulnerable	Attacked	Damaged
Reinforced concrete elements. Corrosion of reinforcing steel.				
Good sealer	No or inadequate sealer	Contaminated	Corrosion of rebars	Cracks, delaminations, spalls.
Painted steel elements. Corrosion.				
Good paint	Brittle paint	Bare metal	Corrosion	Section loss
Steel elements. Fatigue.				
Stress cycles less than fatigue limit	Fatigue endurance adequate for service life.	Fatigue endurance not adequate.	Exhausted. Crack initiation.	Measurable cracks.

Table 7: AASHTO Recommendations and Integrated Condition States for Substructure

	1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Footings					
Scour (probing)				No scour	Scour
Movement, Rotation, Shifting, Settlement				No movement	Movement
Spill through Abutment					
Slope protection instability (scour)				Stable	Unstable
RC Substructure					
Corrosion			No corrosion	Staining	Spalling
Seismic Restraint					
Deterioration, Breakage				No deterioration	Deterioration
Movement				No movement	Movement
Masonry Abutment					
Mortar			Sound mortar	Erosion	Cavities
Stones				No deterioration	Deterioration
Bearings					
Bearing seats				No deterioration	Deterioration
Alignment				Not misaligned	Misaligned
Movement under load				No movement	Movement
Retaining Walls					
Scour, Erosion				No scour	Scour
Deterioration, Cracking				No deterioration	Deterioration
Stability, Cracks in slope behind wall				Stable	Unstable
MSE Walls					
Bulging, Anchor failure				No failure	Failure
Steel Substructure					
Corrosion				No corrosion	Corrosion
Timer Substructure					
Decay, Rot				No decay	Decay
Pile Caps					
Movement, Rotation under load.				No movement	Movement
Rockers Rollers Hangers					
Inclination relative to temperature				Not misaligned	Misaligned
Dolphins and Fenders					
Abrasion				No abrasion	Abrasion
Material deterioration				No deterioration	Deterioration

Table 8: AASHTO Recommendations and Integrated Condition States for Superstructure

	1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Steel beams, girders and box sections					
Fracture critical evaluation		Not critical	Critical		
Fatigue prone		Not prone	Prone		
Corrosion, Loss of section				No loss	Loss
Out of plane bending				Not bent	Bent
Buckling, flanges				Not buckled	Buckled
Continuous wetting of uncoated steel		Dry	Wet		
Salt spray on uncoated steel		No spray	Spray		
Pitting of surface			No pits	Pits	
RC beams and girders					
Cracks			Cracks not significant	Minor cracks	Major cracks
Stems, Disintegration at bearing				Sound	Unsound
Stems, Diagonal cracks			Cracks not significant	Minor cracks	Major cracks
Midspan, Vertical cracks			Cracks not significant	Minor cracks	Major cracks
P/S beams, girders and boxes					
Material deterioration				No deterioration	Deterioration
Cracking			Cracks not significant	Minor cracks	Major cracks
Creep, Humping				No creep	Creep
Pretensioned boxes					
Movement under live load				No movement	Movement
Fascia surfaces on overpass bridges				No collision	Collision
Timber systems					
Splitting				No splits	Splits
Cracking				No cracks	Cracks
Deflection				No deflection	Deflection
Crushing at bearing seats				No crushing	Crushing
Dirt accumulation		No dirt	Dirt		
Timber bridging				Tight	Loose

Table 8: AASHTO Recommendations and Integrated Condition States for Superstructure (Continued)

	1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Steel floor systems					
Fracture critical connections		Not critical	Critical		
Corrosion				No corrosion	Corrosion
Fatigue in floor beams at stringers		Not prone	Prone		
Fatigue in floor beams at main system		Not prone	Prone		
Trusses					
Alignment				No sags	Sags
Compression members. Straightness				Straight	Not straight
Tension members. Fracture critical		Not critical	Critical		
Traffic damage				No collision	Collision
Soundness of bracing				Sound	Unsound
Cables					
Corrosion				No corrosion	Corrosion
Fretting fatigue				No fretting	Fretting
Broken wires				No breaks	Breaks
Vibration No		vibration	Vibration		
Diaphragms					
Members				No deterioration	Deterioration
Gusset plates				No deterioration	Deterioration
Steel connections					
Movement of bolts				No movement	Movement
Movement of connected parts				No movement	Movement
Loss of rivet heads				No loss	Loss
Cracks in welds			Minor cracks	Active cracks	Critical cracks
Pins and hangers					
Fracture critical members		Not critical	Critical		
Free movement				Free	Frozen
Misalignment				Not misaligned	Misaligned
Pack rust			No corrosion	Corrosion	Distortion

(*continued on next page*)

Table 8: AASHTO Recommendations and Integrated Condition States for Superstructure (Continued)

	1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Bearings					
Alignment				Not misaligned	Misaligned
Movement under load				No movement	Movement
Expansion bearings					
Free movement, Function				Free	Frozen
Elastomeric bearing					
Material deterioration				No deterioration	Deterioration
Bulging				No bulges	Bulges
Splitting				No splits	Splits
Pot/Disc bearings					
Deformed elastomer				Not deformed	Deformed
Extruded elastomer				Not extruded	Extruded
Seals and rings				Not failed	Failed
Bearing seat / Pedestal					
Material deterioration				No deterioration	Deterioration
Paint					
Rust pitting			No pitting	Pitting	
Chalking	No chalking	Chalking			
Crazing	No crazing	Crazing			
Staining			No staining	Staining	
Cracks in surface		No cracks	Cracks		
Arches					
Cracking, Movement of supports				No movement	Movement

where x_{Vul} are data from a test for the *Vulnerable* condition state, and T_{Vul} is the threshold. For *Vulnerable* and *Attacked* condition states,

$$\begin{aligned} &If\left(x_{Att} < T_{Att}\right) then\ Vulnerable \\ &If\left(x_{Att} \geq T_{Att}\right) then\ Attacked \end{aligned} \quad \text{(Eq. 3)}$$

where x_{Att} are data from a test for the *Attacked* condition state and T_{Att} is the threshold. For *Attacked* and *Damaged* condition states,

$$\begin{aligned} &If\left(x_{Dmg} < T_{Dmg}\right) then\ Attacked \\ &If\left(x_{Dmg} \geq T_{Dmg}\right) then\ Damaged \end{aligned} \quad \text{(Eq. 4)}$$

where x_{Dmg} are data from a test for the *Damaged* condition state, and T_{Dmg} is the threshold.

All tests should provide consistent assignments of condition ratings. There are two aspects to consider here: variability in measurements, and uncertainty in the meaning of measurements.

Tests are variable. Repeated tests on a single specimen, and tests among a population of specimens in similar condition yield a range of measurements. This range is due to the inherent variability in the test. The difference between a test measurement and the true value of a property is

$$\varepsilon = x_{Test} - x_{Actual} \quad \text{(Eq. 5)}$$

where ε is the error, x_{Test} is the test measurement, and x_{Actual} is the true value of the property. Error may also be expressed a normalized error

$$\varepsilon = \frac{x_{Test} - x_{Actual}}{x_{Actual}} \times 100 \quad \text{(Eq. 6)}$$

The appropriate form of error, absolute or normalized, depends on the test. Some tests exhibit consistent error magnitude over a range of values of interest. Other tests exhibit errors that are consistent fractions of the actual value. There are usually limits on errors. Some properties do not exist as negative-valued quantities (chemical concentration, electrical resistance, elastic modulus, etc.). Errors may be observed only in a certain range of values. Upper limits ε_U and lower limits ε_L are identified.

Variability in tests is expressed as probability density function, $f(\varepsilon)$. For a test measurement, x_i, a condition rating may be assigned by comparison with a threshold T_j, and the probability that the true value exceeds the threshold is computed:

$$\varepsilon_i = x_i - T_j \quad \text{(Eq. 7)}$$

$$\text{Prob}\left[x_{Actual} > T_j\right] = \int_{\varepsilon_L}^{\varepsilon_i} f(\varepsilon) d\varepsilon$$

where x_i is the test measurement and T_j is the threshold for the test. The probability that a threshold is exceeded is the probability that a condition exists. For many tests, errors, ε, appear to be normally distributed (*3*). Limits ε_U and ε_L may be introduced to arrive at truncated normal distributions, or to form Pearson Type 1 distributions (β distributions) (*4*). Type 1 distributions are convenient because the function and its derivatives are continuous. The upper and lower bounds for Type 1 distribution are typically wider than the limits ε_U and ε_L observed in tests. Limits are selected to conform to physical limits (non-negative quantities), and to assure a reasonably high probability that all likely test data are included.

Some properties measured by tests are direct measures of conditions. Other properties are correlated with conditions. Measurement of contaminant concentration is a direct indicator of condition. Some contaminants are identified as causes of damage mechanisms, and the threshold for the contaminant defines condition states. Even so, there is a range of concentrations that do in fact initiate a damage mechanism.

Electrical resistance tests applied to assessment of concrete sealers is an example of a correlated indicator. The property of interest is resistance to chloride ion diffusion. The electrical resistance test is correlated with water permeability of concrete, which itself is related to resistance to chloride ion diffusion. The correlation is not perfect. There is a range of values of electrical resistance that offer no certain indication of effectiveness of sealers.

The variability in correlation of measured properties and element conditions is expressed as a probability density function $g(y)$. Again, there are limits on the range of measured properties, here noted as an upper limit y_U and a lower limit y_L. The probability that a condition exists, given a value y_i of a cause or of a correlated property is computed.

$$\text{Prob}[\textit{Condition Exists}] = \int_{y_L}^{y_i} g(y)dy \qquad \text{(Eq. 8)}$$

The value y_i is the actual value of the property. The available data are x_i from tests. Combining test variability with condition uncertainty, the probability of a condition is

$$\begin{aligned}\text{Prob}[\textit{Condition Exists}] &= \int_{\varepsilon_L}^{\varepsilon_U} f(\varepsilon)\left(\int_{y_L}^{x_i-\varepsilon} g(y)dy\right)d\varepsilon \\ &= \int_{\varepsilon_L}^{\varepsilon_U} f(\varepsilon)G(x_i-\varepsilon)d\varepsilon\end{aligned} \qquad \text{(Eq. 9)}$$

where $G(y)$ is the cumulative probability function for the correlation of a property and a condition. In Eq. 9, y is replaced by the argument $(x_i - \varepsilon)$ using Eq. 5.

Eq. 9 is used to determine the probability of existence of a condition state associated with a threshold T_j.

$$\text{Prob}[\textit{Condition Exists}] = \int_{\varepsilon_L}^{\varepsilon_U} f(\varepsilon)G(T_j-\varepsilon)d\varepsilon \qquad \text{(Eq. 10)}$$

Eq. **10** is an assessment of the threshold *Tj* that is the basis for interpretation of test data. Using Eq. **10**, thresholds can be identified as early, low probability indicators of condition, or as late, high-probability indicators. Shim (*3*) examined a group of tests of monitoring reinforced concrete elements subject to contaminate leading to corrosion of reinforcing steel and reported the probabilities associated with standard thresholds. Using Eq. 10, thresholds T_j for test methods are adjusted as necessary to achieve equal probability of *Condition* among all tests and all state transitions.

EVOLUTION OF CONDITIONS AND PROPERTIES

Some properties change gradually during service life of bridge elements, indicating underlying gradual deterioration. Other properties change abruptly. An example here is half-cell testing for detection of corrosion activity in reinforced concrete elements. Electrical potentials are different and more negative for embedded rebars that are corroding than for those that are not. Electrical potentials shift abruptly to values that are more negative when rebars begin to corrode. For electrical potentials and other properties that change abruptly, there are two distinct distributions of measurements. The first, $a(y)$, is the distribution of values of the property for elements that are in condition state, k. The second, $b(y)$, is for elements in the next condition state, $k + 1$.

The probability of an element being in condition state k, as a function of value y of a property, is

$$\text{Prob}[\textit{Condition } k] = \frac{a(y)}{a(y) + b(y)} \qquad \text{(Eq. 11)}$$

The probability of an element being in condition state $k + 1$, as a function of property y, is

$$\text{Prob}[\textit{Condition } k + l] = \frac{b(y)}{a(y) + b(y)} \qquad \text{(Eq. 12)}$$

Eq. **11** and Eq. **12** yield cumulative probabilities. Eq. **12** in particular is a $G(y)$ function, an expression of the probability of existence of the $k + 1$ condition state as a function of a property y. This $G(y)$ function can be used to evaluate and to adjust thresholds for interpretation of test data.

$$\text{Prob}[\textit{Condition Exists}] = \int_{\varepsilon_L}^{\varepsilon_U} f(\varepsilon) \frac{b(T_j - \varepsilon)}{a(T_j - \varepsilon) + b(T_j - \varepsilon)} d\varepsilon \qquad \text{(Eq. 13)}$$

AGE IN SERVICE

Some properties are related to rates of deterioration processes. Tests of material quality, sealers, membranes, etc. are tests for protection of elements. Evaluations of protection may indicate that aggressive agents can enter, but that rates are slow and therefore acceptable. In service, it is possible that the protection remains in adequate condition. However, over time elements may advance to a contaminated, vulnerable condition. Once elements are contaminated, it is not appropriate to use a test of the protection system alone, and to declare that the element is in a protected condition state. The direct comparison data to thresholds, Eq. **1**, is modified to include a consideration of age of elements.

For tests related to rates of deterioration, a process function, $h(y_1,y_2)$, is formed. $h(y_1,y_2)$ is an expression of the physical process at work in the element, and it yields the expected time for properties to advance from value y_1 to value y_2. The time to transition to the next condition state is computed as

$$t = h\left(y, T_j\right) \qquad \text{(Eq. 14)}$$

where t is the time to reach threshold, T_j. Process functions, $h()$, are, variously, diffusion laws, or fatigue damage accumulation laws, or other expressions of accumulating deterioration.

The condition rating is determined by comparing the time, t, to the age of the element. It is possible in this way to identify three condition states: *Protected*, *Exposed* and *Vulnerable*. Elements are *Vulnerable* when the age of the element exceeds the expected time to reach the threshold, T_j. Elements are *Exposed* if the remaining time to reach the threshold is not greater than the time to threshold for a newly constructed, unprotected element. Elements are *Protected* if the time to reach the threshold is greater still.

$$\begin{aligned} &t_i = h\left(y_i, T_j\right) \\ &If\left(t_i - Age - t_{Exp} > 0\right) Protected \\ &If\left(t_i - Age - t_{Exp} \leq 0\right) Exposed \\ &If\left(t_i - Age \leq 0\right) Vulnerable \end{aligned} \qquad \text{(Eq. 15)}$$

where *Age* is the age of the element, t_{Exp} is the time to threshold T_j for a new, unprotected element.

DETERIORATION MODELING

Test data are used to calibrate models of deterioration for use in bridge management systems. Test data may be introduced as condition ratings. Condition states are linked to physical properties, and so the mean time for transition in condition ratings can be interpreted as the mean endurance of elements at particular stages (*5*).

Test data can be used directly to calibrate deterioration models. Test data are used together with process functions, $h()$, to estimate the time to transition to the next condition state. This time is used to calibrate the deterioration model in a bridge management system. First, the ages of elements, and current value, y, of properties are used to calibrate the process function, $h()$.

$$t_{State} = h^*\left(y_{Initial}, y_t\right) \qquad \text{(Eq. 16)}$$

where t_{State} is the number of years the element has been in the current condition state, $y_{Initial}$ is the value of the property at the time the element first entered the current condition state, y_t is the value of the property at the present time, and h^* is a process function that has been calibrated for the observed change in property, $y_{Initial}$ to y_t over the interval t_{State}.

The calibrated function h^* is used to estimate the remaining time to transition to the next condition state.

$$t_{Trans} = h^*\left(y_t, T_j\right) \qquad \text{(Eq. 17)}$$

The time of residence of elements in a condition state is then the sum of the time passed, and the time remaining.

$$t_{Residence} = t_{State} + t_{Trans} \qquad \text{(Eq. 18)}$$

The time of residence is used to calibrate a model in a bridge management system. If Markov chains are used in the management system, then the transition probability, P, is set as

$$P = 1 - \frac{1}{t_{Residence}} \qquad \text{(Eq. 19)}$$

SUMMARY

Data from tests can be interpreted as condition ratings. This provides the basic link between bridge testing and bridge management. The interpretation requires an examination of thresholds for test data and of definitions of condition states. The approach, though developed for NDE field tests, is generally applicable to materials acceptance tests, field tests and other observations or determinations in bridge inspections.

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