Maintenance and Repair of Bridges Using a Performance-Based Design Model

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***Abstract*—Thirty-six percent of the USA bridges, over 224,000, need repair work, and over 78,800 bridges should be replaced. Bridges have been subjected to constant, sustainable and sequential progress in the last decade. The need to extend the service life of existing prominent bridges and a better perceptive of the deterioration mechanisms in concrete has led to efforts to develop a rational methodology for maintaining concrete. This research aims to treat the subject of maintenance of concrete bridges on a basis for developing specific quantitative parameters, specifications, and manuals for different concrete bridges. The paper imparts the rehabilitation of an under-construction regional bridge as a case study for applying the suggested maintenance system. It presents the outline of the design system for the bridge retrofitting based on the performance-based design to satisfy an adequate required level concerning all required performance items, including structural safety and serviceability. An impersonal evaluation technique relevant to Value Engineering is implemented to express the convenience of the repair method. The concept is to convert any criteria involved in measurable values on the same scale, whether the decisive factor is structural integrity, ease of construction, sustain of traffic service, environmental hazards and repairs cost. Steps forward in numerical analysis techniques and the evolution of precise simulation methods are powerful tools. It releases the doubtful sense of the designer to the requirements of his structures, taking into account the required precision of the constitutive modeling and its construed parameters.**

Keywords*— bridges; serviceability; repair; performance index; performance-based design

I. INTRODUCTION

The design systems of reinforced concrete bridges are shifting to performance-based design systems that seem to be current worldwide. In the new systems, highly developed analytical methods (numerical methods) are crucial in order to check in an unwavering approach whether the performances of bridges indisputably satisfy the required performance [1].

The performance of bridges is critical to the overall performance of the highway transportation system in the United States. However, many critical aspects of bridge performance are not well understood. The reasons for this include the extreme diversity of the bridge infrastructure, the widely varying conditions under which bridges serve, and the lack of reliable data needed to understand performance [2]. Thirty-six percent of the United States bridges, over 224,000, need repair work, and over 78,800 bridges must be replaced. More than 43,500 bridges are rated in a poor condition and classified as "structurally deficient" [3]. Bridges have been exposed to constant, sustainable, and consecutive progress in the last decade. The need to spread the service life of existing prominent bridges and an improved perceptive of the deterioration mechanisms in concrete has directed efforts to develop a coherent methodology for maintaining concrete.

The highway bridge infrastructure in the United States is extensive and diverse. The term bridge is defined by the National Bridge Inspection Standards (NBIS): A structure including supports created over a depression or obstruction such as a highway, railway, or water and having a track or passage for carrying traffic or additional moving loads and having an opening measured along the center of the roadway of more than 20 ft. [4]. A brief aspect of data from the National Bridge Inventory (NBI) reveals this vital public asset.

The 2011 NBI contains records for 605,098 bridges, of which 132,150 are classified as tunnels or culverts [5]; The remaining 472,948 are single- or multi-span bridges separating vehicular traffic from other traffic or some topographical feature, usually a stream or river. These bridges range from the average highway overpass structure to "signature bridges," such as the Golden Gate Bridge, the Brooklyn Bridge, or the Sunshine Skyway. Within this range, the diversity of the bridge infrastructure in terms of age and design parameters (including structural type, construction materials, width, and length) is extensive. NBI records describe bridges using many different attributes or parameters. Table I provides an abbreviated list of these characteristics and indicates the different types in the NBI for each [4].

TABLE I. DIVERSITY OF BRIDGE CHARACTERISTICS

NBI Item	Number of Types
Kind of material, main span and/or approach span	10
Structure type, main span and/or approach span	23
Design load	10
Bridge posting	6
Deck structure type	9
Wearing surface	9
Membrane	5
Protective system	9

The sub-committee 307 under the Concrete Committee in the Japan Society of Civil Engineers drafted the new design system for rehabilitating existing concrete bridges in 1998 [6][7]. Bridge deterioration models are an essential component of bridge management systems (BMS), it allows the prediction of future bridge performance and requirements. Existing BMS, for example, Pontis 1993 model bridge deterioration as the decline of condition rating over time [8]. The design system is based on performance-based design, which is accepted as the appropriate design perception for general concrete bridges in the next decade. The proposed design system consists of the basic framework and the rehabilitation design manual. The former part contains the basic concept and standard descriptions. At the same time, the latter recommends equations to verify bridge rehabilitation performances with external cable, carbon fiber materials, steel plates, and concrete. This paper outlines the former part, i.e., the basic outline of the proposed design system. Each bridge in the 2011 NBI is described by an extensive set of characteristics, parameters, and operating conditions, all of which have some impact on some aspects of the performance of the bridge. Table II lists the most important of these items [4].

In addition, the bridge's age is a significant contributing factor to its current and future performance. However, the simple age in years does not represent a precise measure of the impact of age on performance. The chronological age does not accurately reveal essential knowledge about the cumulative degradation of material properties, the cumulative amount of Damage from live loads, and past maintenance and repair history. The average age of all NHS bridges in the NBI is 36.3 years; the average age of all non-NHS bridges is 42.3 years, and the average age of all bridges is 41.0 years. Fig. 1 shows the diversity in age of bridges with a histogram of bridges still in service that were built within 5-year periods [5].

Other critical factors affecting bridge performance are the type, frequency, and effectiveness of preservation, maintenance, repair, and rehabilitation actions performed on bridges by the owner or entity charged with maintenance responsibility. Various agency types own bridges on public highways at different levels of government and by railroads, toll authorities, and other private entities. Table III shows the number of different types of entities that have maintenance responsibilities for bridges on public highways [4].

Based on the 2011 NBI data, the bridge infrastructure in the United States can be further described in Table IV, Fig. 2, and Table V [5].

TABLE II. DIVERSITY OF BRIDGE CHARACTERISTICS, PARAMETERS, AND OPERATING CONDITIONS

Item	NBI Item Numbers
Kind of material, main span and/or approach span	43A, 43A
Structure type, main span and/or approach span	43B, 44B
Horizontal geometry and skew	47, 51, 52, 55A, 55B, 56
Vertical clearances over and under the bridge	53A, 54A, 54B
Design load	31
Bridge posting	70
Deck structure type	107
Wearing surface	108A
Membrane	108B
Protective system	108C
Type of joints and bearings	Data not available in NBI
Type of foundation	Data not available in NBI
Local environment	Data not available in NBI
Local climate patterns	Data not available in NBI
Maintenance, repair, and rehabilitation history	Data not available in NBI
Permit loads history	Data not available in NBI
Annual ADT and truck traffic	29, 109
Safety features	33, 36
Maintenance responsibility, owner	21, 22
Functional class of inventory route	26
Channel and channel protection	61
Critical feature	92A, 92B, 92C

inspection	
Scour critically	113

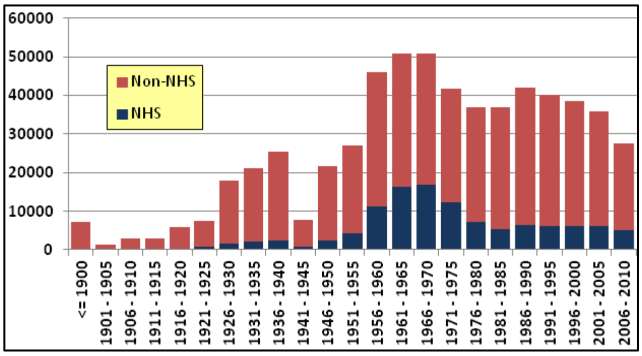

Fig. 1. *Age distribution of all bridges in the United States*

TABLE III. TYPES OF ENTITIES WITH BRIDGE MAINTENANCE RESPONSIBILITY

Entity Category	Number of Different Types
State and local highway agencies	4
Other State and local agencies	4
Private owners	4
Federal agencies	15

TABLE IV. TYPES OF ENTITIES WITH BRIDGE MAINTENANCE RESPONSIBILITY

Functional Class	No.	%age	Deck Area (ft^2)	No.
Rural, interstate	20,434	4.32	261,976,842	7.35
Rural, other arterials	51,304	10.84	540,109,441	15.16
Rural, collector	104,701	22.13	446,633,350	12.53
Rural, local	173,573	36.68	339,994,461	9.54
Subtotal, rural	**350,012**	**73.97**	**1,588,714,083**	**44.58**
Urban, interstate	26,774	5.66	697,385,694	19.57
Urban, other arterials	59,782	12.63	1,031,374,442	28.94
Urban, collector	14,812	3.13	117,799,536	3.31
Urban, local	21,785	4.60	128,570,034	3.61
Subtotal, urban	**123,153**	**26.03**	**1,975,129,705**	**55.42**
Total, rural and urban	**473,165**	**100.00**	**3,563,843,788**	**100.00**

Note. The Table does not include culverts and tunnels.

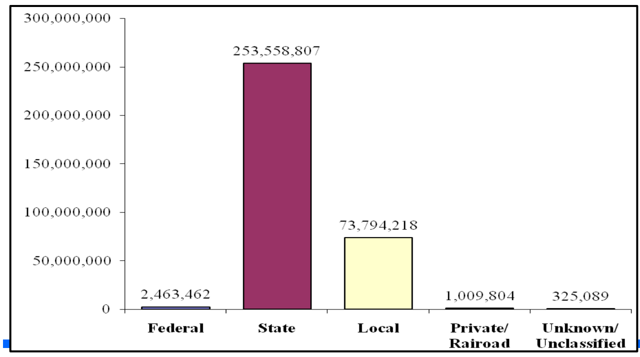

Fig. 2. *Deck area (m^2) of bridges by owners*

TABLE V. NUMBERS AND PERCENTAGES OF BRIDGES AND DECK AREA BY OWNER

Bridge Owner	No. of Bridges	%age of All Bridges	Deck Area (ft^2)	%age of All Deck Areas
State highway agency	214,058	45.23	2,589,978,541	72.66
State park, forest, or reservation agency	884	0.19	1,944,059	0.05
Other State agencies	1,080	0.23	10,281,397	0.29
State toll authority	6,861	1.45	127,080,287	3.57
Total, State Bridges	**222,883**	**47.09**	**2,729,284,284**	**76.57**
Other Federal agencies (not listed below)	52	0.01	1,308,741	0.04
Indian tribal government	1	0.00	312	0.00
Bureau of Indian Affairs	704	0.15	2,291,701	0.06
Bureau of Fish and Wildlife	278	0.06	371,064	0.01
U.S. Forest Service	3,579	0.76	4,647,426	0.13
National Park Service	1,150	0.24	6,227,557	0.17
Tennessee Valley Authority	35	0.01	1,072,268	0.03
Bureau of Land Management	1	0.00	1,518	0.00
Bureau of Reclamation	321	0.07	797,735	0.02
Corps of Engineers (Civil)	441	0.09	5,438,014	0.15
Corps of Engineers (Military)	17	0.00	659,440	0.02
Air Force	24	0.01	21,765	0.00
Navy/Marines	151	0.03	1,260,518	0.04
Army	556	0.12	2,149,574	0.06
National Aeronautics and Space Administration	0	0.00	0	0.00
Metropolitan Washington Airports Service	23	0.00	268,839	0.01
Total, Federal bridges	**7,333**	**1.55**	**26,516,484**	**0.74**
County highway agency	187,902	39.70	464,876,596	13.04
Town or township highway agency	23,563	4.98	41,438,795	1.16
City or municipal highway agency	27,998	5.92	235,181,884	6.60
Local park, forest, or reservation agency	64	0.01	139,285	0.00
Other local agencies	1,162	0.25	15,556,768	0.44
Local toll authority	582	0.12	37,121,035	1.04
Total local bridges	**241,271**	**50.98**	**794,314,352**	**22.28**
Private (other than railroad)	433	0.09	6,549,226	0.18
Railroad	896	0.19	4,320,332	0.12
Total private/railroad bridges	**1,329**	**0.28**	**10,869,440**	**0.30**
Unknown	363	0.08	1,901,929	0.05
Unclassified	89	0.02	1,597,300	0.04
Total, unknown/ unclassified bridges	**452**	**0.10**	**3,499,229**	**0.10**

II. Objectives and Scope of Research

While various techniques and systems can be used for bridge rehabilitation, picking the most appropriate rehabilitation method is one of the key success factors. Therefore, the primary objective of this research is to develop a Performance-Based Design Management Model (PBDMM) under the umbrella of recent management techniques.

The research is divided into several phases. First, a review of the state-of-the-art of several performance indicators used to evaluate bridge performance is conducted. Second, a review of the state of the practice in bridge rehabilitation systems is undertaken. Third, a classification of bridge performance indicators is made depending on the approach (deterministic, semi-probabilistic, or probabilistic) and level of concern (cross-section, component, or system). These phases are outlined in the proposed PBDMM. The various technologies are evaluated through these reviews, and the most promising technologies and practices are included in the proposed model. Finally, recommendations are provided on the use of the model for the rehabilitation of existing bridges.

III. Proposed Performance-Based Design Management Model (PBDMM)

For Bridge structures, a set of performance items is required quantitatively depending on the bridge's category, usage, and importance. In the proposed system, the performance of bridges is evaluated as a function of time, considering time-dependent deterioration due to loading and environmental assault. Fig. 3 shows the proposed performance-based design management model, which considers the required performance corroboration of the bridge structure. This model consists of 10 modules, as follows:

1) Bridge Condition Assessment Module
2) Measurement Module
3) Comparison Module
4) Options Module
5) Analysis Module
6) Design Module
7) Optimization Module
8) Design Module
9) Rehabilitation Module
10) Re-measure Module
11) Final Assessment Module

1) Module (1): Bridge Condition Assessment

The existing R.C. bridge's condition assessment aims to determine whether the bridge will function safely over a specified residual service life. Guidelines for the assessment of existing bridges have been developed in many countries. They are commonly separated into phases, starting with a preliminary evaluation, followed by a detailed investigation, an expert investigation, and finally, an advanced assessment, depending on the structural condition of the investigated bridge [10]. Based on the different applications of the selected articles, the relevant techniques are classified into five categories, as shown in Fig. 4 [9][10].

2) Module (2): Measurement

To practice recital verification, both performances of bridges and requirements should be expressed quantitatively. Hence, each performance item listed in Table VI should be symbolized by a corresponding physical variable which can be evaluated through available computational methods. This variable is called a performance index. Table VI shows an example of performance indices for the selected performance items in this proposed PBDMM. Equation (1) measures the bridge's general condition ratings (GCRs) or performance/health index.

$$\text{Bridge GCRs (Performance/Health Index)} = \mathrm{SC.w1} + \mathrm{FC.w2} + \mathrm{TC.w3} + \mathrm{CC.w4} \quad (1)$$

3) Module (3): Comparison

BI general condition ratings (GCRs) are implemented to define the existing bridge or culvert as compared to the as-built condition. The bridge materials are considered, in addition to the physical condition of the bridge deck, substructure, and superstructure components. This information is used to define GCRs on a numerical scale. The scale ranges from 0 (failed condition) to 9 (excellent condition), as designated in the FHWA Coding Guide Table VII and Equation (2) [2].

$$1 \leq \text{C.R.} \leq 9 \quad (2)$$

4) Module (4): Analysis

The NBI condition ratings are well established after almost four decades of use in assessing the current condition of the major components of bridges being inventoried and inspected. The same is true of NBI appraisal ratings for assessing functional capacities. Changes in these ratings over time reflect the general performance of the bridge. The ratings are used to classify bridges as deficient or not deficient [4].

Bridges with low NBI condition or appraisal ratings are flagged and classified as follows:

- **SD**: A highway bridge is classified as structurally deficient if item 58 (deck), item 59 (superstructure), item 60 (substructure), or item 62 (culvert) is rated "poor" condition or worse (coded 4 or lower in the NBI rating scale). A bridge can also be classified as S.D. if its load-carrying capacity is significantly below current design standards, with item 67 (structural evaluation appraisal) coded 2 or lower, or if item 71 (waterway adequacy) for the feature below the bridge is coded 2 or lower.
- **F.O.**: A highway bridge classified as functionally obsolete is not S.D., but its design is outdated. The bridge may have a lower load-

carrying capacity, narrower shoulders, or smaller clearance underneath than bridges built to the current standards. Classification as F.O. is triggered by a code of 3 or lower for item 68 (deck geometry appraisal), item 69 (under-clearances, vertical and horizontal), or item 72 (approach roadway appraisal). A bridge is also classified as F.O. if item 67 (structural evaluation appraisal) or item 71 (waterway adequacy appraisal) is coded 3.

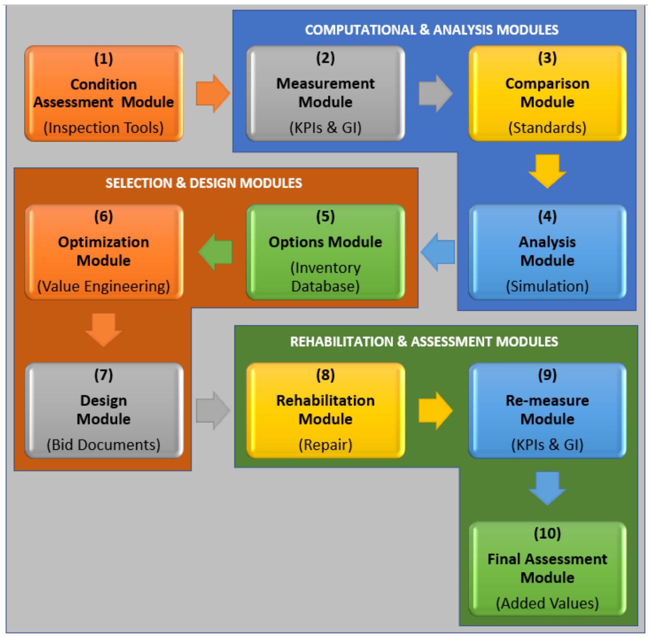

Fig. 3. *Proposed performance-based design management model*

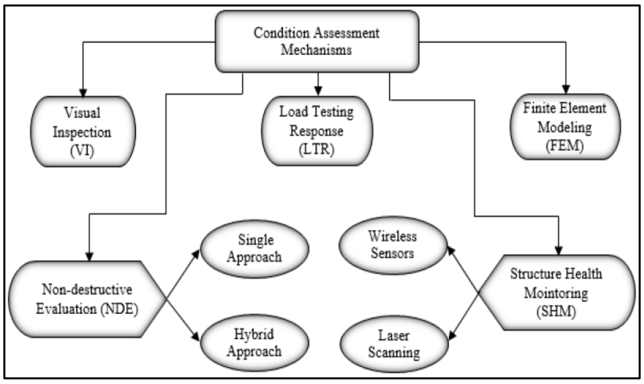

Fig. 4. *Condition assessment mechanisms of reinforced concrete bridges*

5) Module (5): Feasible Rehabilitation Strategies

This model establishes guidelines for the evaluation, preservation, rehabilitation and replacement inventory database of existing concrete bridges. The determination of the most appropriate intervention for existing bridge decks is primarily based on the following factors [11]:

- Depth and concentration of chloride penetration into the deck surface
- Area of delamination, spalls, and patches (compromised area)
- The extent of corrosion in existing steel
- Extent and width of cracks
- Condition of the bottom of the deck
- Presence of reactive aggregates susceptible to alkali-silica reaction (ASR)
- Strength of concrete
- Permeability of concrete

Table VIII shows the Hierarchy of deck Treatment options (least protective to most protective) [11]. Table IX shows the deck decision matrix for concrete decks [12][13].

The cost analysis of preserving the existing concrete superstructure should consider the following as applicable [14]:

- Preserving or replacing the deck
- Effects associated with the elimination of deck joints
- Repairing prestressed or reinforced concrete beams and concrete slab spans
- Impact strengthening of prestressed or reinforced concrete beams using carbon fiber reinforcement on bridge spans with a history or high potential of vehicular impacts
- Mitigating effects of alkali-silica or alkali-carbonate reactive aggregate
- Replacing severely corroded or non-functional bearings
- Adding redundancy
- Temporary support of the superstructure due to rehabilitating or replacing the substructure (e.g., blocking and jacking to perform seat repair or towers to support the superstructure)
- Seismic retrofit, if needed
- Replacing or eliminating approach slabs that extend backward. In these cases, the joint material bears directly against the bridge deck and end of the approach slab. If settlement occurs, the joint opens up.

6) Module (6): Optimization by Value Engineering

The concept of the bridge health index is based on a ratio of the current element value to the total element value. The health index formulated ranges between 0% and 100%. The NBI deck rating of 6.9 may be comparable to a health index of 84%. Many state agencies use such a health index to manage their bridge structures. Fig. 5 shows the flowchart of optimizing the rehabilitation design system of bridges. Table X shows the Evaluation Requirements and Recommendations for Concrete Decks [15].

7) Module (7): Design

Fig. 6 to 9 show sample details for the Flexible Link Slab, Deck Extension, Virginia Micro-Abutment and Virginia Alternate Micro-Abutment [16][17].

TABLE VI. PERFORMANCE INDICES FOR THE SELECTED PERFORMANCE ITEMS IN THE PROPOSED PBDMM

Category	Item Description	Indicator Designation	Indicator Method	Level	Indicator Formula
Structural Condition (S.C.)	Indicating damage level	Condition State (C.S.)	Deterministic	Component	1 ≤ CS ≤ 5
	Indicating the instantaneous probability of failure	Probability of Failure (Pf)	Probabilistic	Section, Component & System	$P_f = P(M(t) \leq 0) = \int_0^{\infty} F_R(x) f_Q(x) dx$ *R* = Random resistance in a specific failure mode. *Q* = Random load effect in the same failure mode. *F.R.* (*x*) = Cumulative distribution function of *R*. *fQ*(*x*) = Probability density function of load effect *Q*.
	Providing a design margin over theoretical design capacity	Safety Factor in Allowable Stress Design (S.F.)	Deterministic	Section & Component	$SF = \frac{\sigma_u}{\sigma_{all}}$ σ_u = Maximum usable stress. σ_{all} = Allowable stress.
	If *R* is greater than *Q*, a margin of safety exists.	Partial Factors Used in LRFD (Φ,γ)	Semi-Probabilistic	Section & Component	$\phi R_n \geq \gamma_D Q_{Dn} + \gamma_L Q_{Ln} + \ldots$ ϕ = Resistance factor associated with nominal resistance R_n. γ_D, γ_L = Partial load factors associated with the dead and live loads effects Q_{Dn} and Q_{Ln}.
	Load modifier factor (η) relating to ductility, redundancy and operational importance	Load Modifier Factor Used in LRFD (η_i)	Semi-Probabilistic	Component & System	$\phi R_n \geq \sum \eta_i \gamma_i Q_i$ $\eta_i = \eta_D \eta_R \eta_I \geq 0.95$ $\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \leq 1.0$ η_D = Factor relating to ductility. η_R = Factor relating to redundancy. η_I = Factor relating to operational importance.
	A theoretical factor by which a set of loads acting on the structure cause it to collapse	Collapse Load Multiplier (λ)	Deterministic	System	$Q_U = \lambda_o (Q_D + Q_L)$ **for Proportional Loading** $Q_U = Q_D + \lambda_L Q_L$ **for Combined Loading** $Q_U = \lambda_D Q_D + \lambda_L Q_L$ **for Arbitrary Loading**
	The ratio of the load-carrying capacity of the intact structure to the applied load	Reserve Strength Factor (R1)	Deterministic	Component & System	$R_1 = \frac{C}{Q}$
	Measuring the strength of the system in damaged condition compared to the intact system	Residual Strength Factor (R2)	Deterministic	Component & System	$R_2 = \frac{C_d}{C}$
	Varies between 1, when the damaged structure has zero capacity, and 0, when	Redundancy Factor (R0)	Deterministic	System	$R_0 = \frac{1}{1 - R_2}$

	it does not have any reduction in load-carrying capacity				
	Loss in the cross-sectional area of a component	Damage Factor (D)	Deterministic	Section	$D = 1 - \frac{a_d}{a}$ a_d = Cross-sectional area of the damaged portion of the bridge component. a = Intact cross-sectional area of the bridge component.

Category	Item Description	Indicator Designation	Indicator Method	Level	Indicator Formula
Structural Condition (S.C.)	Measuring the reserve capacity, which can be defined as the availability of warning before structural collapse occurs	Redundancy Index (R.I.)	Probabilistic	System	$RI_1 = \beta_{\text{intact}} - \beta_{\text{damaged}}$ $RI_2 = \frac{\beta_{\text{intact}}}{\beta_{\text{intact}} - \beta_{\text{damaged}}}$ $RI_3 = \frac{P_{f(dmg)} - P_{f(sys)}}{P_{f(sys)}}$ β_{intact} = RI of the intact system. $\beta_{damaged}$ = RI of the damaged system. $P_{f(dmg)}$ = Probability of damage occurrence $P_{f(sys)}$ = Probability of system failure.
	One of the key measures used to capture the essential feature of damage-tolerant structures	Vulnerability (V)	Probabilistic	System	$V = \frac{P(r_d,Q)}{P(r_0,Q)}$ r_d = A particular damaged state. r_0 = An undamaged system state. Q = Prospective loading. $P(r_d, Q)$ = Probability of failure in the damaged state. $P(r_0, Q)$ = Probability of failure in the pristine state.
	Damage tolerance as reciprocal of *V*	Damage Tolerance (Dt)	Probabilistic	System	$D_t = \frac{1}{V} = \frac{P(r_0,Q)}{P(r_d,Q)}$
	Defining the ability of bridge component or entire bridge to sustain large deformations without collapse	Ductility (Δ)	Probabilistic	System	$\Delta = \Delta_c - \Delta_{el}$ Δ_c = Deformation at collapse. Δ_{el} = Deformation associated with the limit of elastic range.
	The ability of a structure to prevent failure progression	Robustness (R.O.)	Probabilistic	System	*R.O.* is one of the key measures in the field of progressive collapse and damage-tolerant structures
	Reduce probabilities of failure, consequences of failure, and the time for recovery	Resilience (RE)	Probabilistic	System	*The functionality of an infrastructure system can measure RE* after a disaster and by the time it takes for a system to return to pre-disaster levels of performance

Functionality Condition (F.C.)	Represents how much of bridge cross-section, component, or overall system capacity is held in reserve at a point in time	Margin of Safety (M)	Probabilistic	Section, Component & System	$M = R - Q$ R = Random variable representing the resistance effect. Q = Random variable representing the load effect.
	Measures the time-dependent margin of safety	Time-Dependent Margin of Safety (M(t))	Probabilistic	Section, Component & System	$M(t) = R(t) - Q(t)$ t = Time. R = Time-dependent variable representing the resistance effect. Q = Time-dependent variable representing the load effects.
	Measure the reliability of a bridge index	Reliability Index (β)	Probabilistic	Section, Component & System	$\beta = \frac{E(R) - E(Q)}{\sqrt{\sigma^2(R) + \sigma^2(Q)}}$ $E(R)$ = Mean value of the resistance effect. $E(Q)$ = Mean value of the load effect. $\sigma(R)$ = Standard deviation of the resistance effect. $\sigma(Q)$ = Standard deviation of the load effect.

Category	Item Description	Indicator Designation	Indicator Method	Level	Indicator Formula
Functionality Condition (F.C.)		Hazard rate h(t)	Probabilistic	Component & System	
		Cumulative hazard rate H(t)	Probabilistic	Component & System	
Sustainability Condition (T.C.)	Failure and survival are complementary events	Probability of Survival (Reliability) (Ps)	Probabilistic	Section, Component & System	$P_s = 1 - P_f$
	The loads due to natural phenomena such as earthquakes, storms, and high winds	Return Period (Ť)	Probabilistic	Section, Component & System	$\bar{T} = E(T) = p(1 + 2q + 3q^2 + \ldots)$ p = Probability of occurrence of the event. q = Corresponding probability of nonoccurrence (therefore, $q = 1 - p$).
	The probability of failure within a certain period	Cumulative Time Probability of Failure (F(t))	Probabilistic	Component & System	$F(t_f) = P(T_f \le t_f) = \int_0^{t_f} f(u)du$ $F(t_f)$ = Area under the probability density function $f(u)$ of the time to failure from t_0 to t_f.
	The probability that a component or system survives until time t	Cumulative Time Probability of Survival (S(t))	Probabilistic	Component & System	$S(t) = 1 - F(t) = P(T > t) = \int^{\infty} f(u)du$ $S(t)$ = Area under the probability density function $f(u)$ of the time to failure of t_f to infinity.
	Time-variant redundancy indices	Time-Variant Redundancy Index (RI(t))	Probabilistic	System	$RI_1(t) = \frac{P_{y(sys)}(t) - P_{f(sys)}(t)}{P_{f(sys)}(t)}$ $P_{y(sys)}(t)$ = System probability of first yield at time t. $P_{f(sys)}(t)$ = Probability of system failure at time t. $RI_2(t) = \beta_{f(sys)}(t) - \beta_{y(sys)}(t)$ $\beta_{y(sys)}(t)$, $\beta_{f(sys)}(t)$ = Reliability indices
Costs Condition (CC)	The proper allocation of resources can be achieved by minimizing the total expected cost while keeping structural safety at a desired level	Life-Cycle Cost	Probabilistic	System	$C_{ET} = C_T + C_{PM} + C_{INS} + C_{REP} + C_F$ C_{ET} = Expected life-cycle cost. C_T = Initial design/construction cost. C_{PM} = Expected cost of routine maintenance. C_{INS} = Expected cost of performing inspections. C_{REP} = Expected cost of repairs. C_F = Expected cost of failure.
	The function of the probability of occurrence of adverse event A, P(A), and the consequence of this event, K	Risk (Ɽ)	Probabilistic	System	$\Re = P(A) \bullet K$ The uncertainties in both $P(A)$ and K will carry over in calculating $\Re$

TABLE VII. PERFORMANCE INDICES FOR THE SELECTED PERFORMANCE ITEMS IN THE PROPOSED PBDMM

Code	Description	Common Actions
9	**EXCELLENT CONDITION**	Preservation/Cyclic Maintenance
8	**VERY GOOD CONDITION**—No problems noted.	
7	**GOOD CONDITION**—Some minor problems.	
6	**SATISFACTORY CONDITION**—Structural elements show some minor deterioration.	Preservation/ Condition-Based Maintenance
5	**FAIR CONDITION**—All primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour.	
4	**POOR CONDITION**—Advanced section loss, deterioration, spalling, or scour.	Rehabilitation or Replacement
3	**SERIOUS CONDITION**—Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.	
2	**CRITICAL CONDITION**—Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present, or scour may have removed substructure support. Unless closely monitored, the bridge may have to be closed until corrective action is taken.	
1	**IMMINENT FAILURE CONDITION**—Major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic, but corrective action may put it back in light service.	
0	**FAILED CONDITION**—Out of service. Bridge is beyond corrective action.	

TABLE VIII. HIERARCHY OF DECK TREATMENT OPTIONS (LEAST PROTECTIVE TO MOST PROTECTIVE)

Rank	Deck Treatment
1	Patching - Type B and Type C
2	Crack Sealing with Mesh, Polymer Fill, V Groove or Epoxy Injection
3	Epoxy Overlay
4	Asphalt Overlay with Approved Membrane
5	Rotomill and Rigid Overlay
6	Shallow Hydromill and Rigid Overlay
7	Deep Hydromill and Rigid Overlay
8	Replace Deck

TABLE IX. DECK DECISION MATRIX: CONCRETE DECKS

Worse of These		Condition Category	Year Built	Evaluation Results	Minimum Required Action
Deck GCR	% CA				
7 – 9	≤ 5	Good	Prior to 2003	Recommended, but Not Required	Patch, Epoxy Overlay, Fill Cracks[3], Clean Drains and Sweep/Wash Annually
			2003 or later	Recommended, but Not Required	Patch, Fill Cracks[3], Clean Drains and Sweep/Wash Annually
6	≤ 10	Satis-factory	Any	CA < 5% & CF < 1”	Patch and Epoxy Overlay
				CA ≤ 10% & CF ≤ 1.5”	Patch and Rigid Overlay on Rotomilled Substrate
				No Evaluation or CF[5] >1.5”	Rigid Overlay on Shallow Hydromilled Substrate
5	≤ 15	Fair[4]	Any	CF[5] ≤ Average Cover Depth of Top Bar Mat	Rigid Overlay over Shallow Hydromilled Substrate
				4” > CF[5] ≥ Avg. Cover Depth of Top Bar Mat	Rigid Overlay over Deep Hydromilled Substrate
≤4	≤ 20	Poor[4]	Any	CF[5] ≤ Average Cover Depth of Top Bar Mat	Rigid Overlay over Shallow Hydromilled Substrate
				4” > CF[5] ≥ Avg. Cover Depth of Top Bar Mat	Rigid Overlay over Deep Hydromilled Substrate
Any	Any	Any	Any	CF[5] > 4”	Replace Deck
Any	Any	Any	Any	Spalls - deck bottom >3%	Replace Deck
Any	Any	Any	Any	Reactive Aggregates Present & Cl > 0.02 in/yd	Replace Deck
Any	Any	Any	Any	f_c’ ≤2,400 psi (average)	Replace Deck
Any	Any	Any	Any	Cost to Rehab or Repair > 65% of Replace Cost	Replace Deck

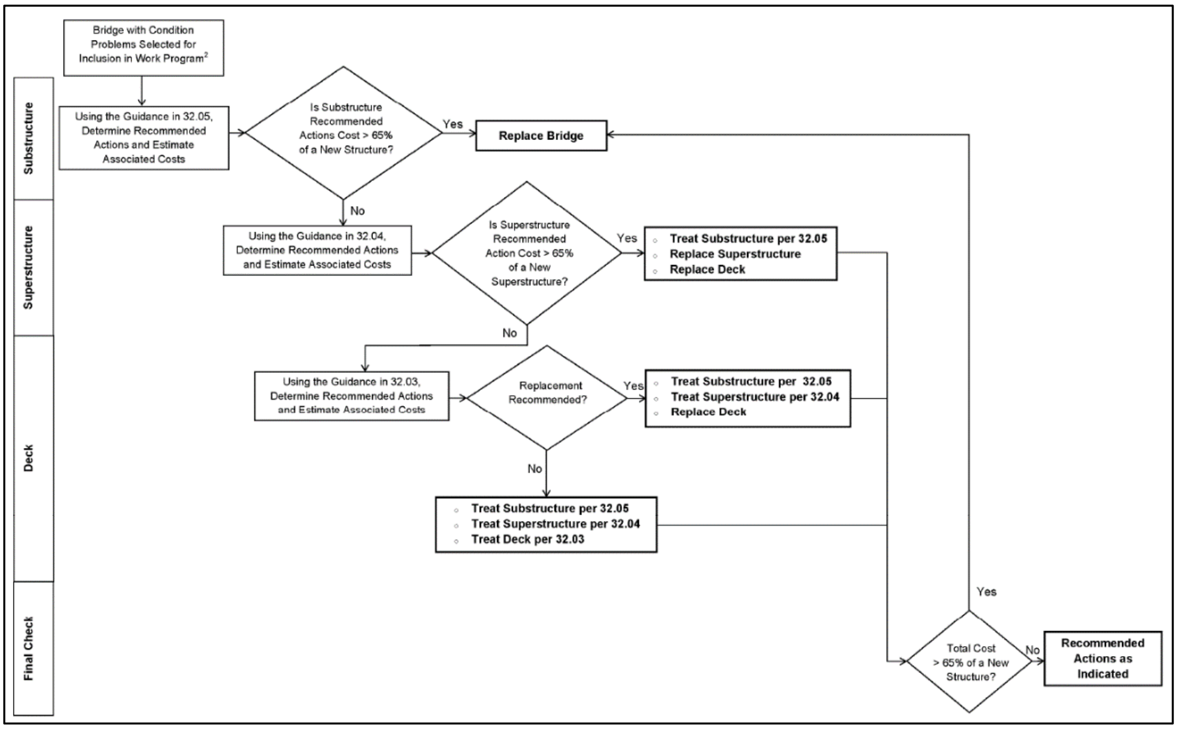

Fig. 5. *Flowchart of optimizing the rehabilitation design system of bridges*

Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 10 Issue 2, February - 2023

TABLE X. DECK DECISION MATRIX: CONCRETE DECKS

Condition Category	Test Type	Minimum Frequency or Number	Locations	Recommended or Required
Good	Visual and Delamination Survey	Entire Deck	Entire Deck	Recommended
	Half Cell Potential	5' x 5' Grid	Entire Deck	Recommended
Satisfactory	Visual and Delamination Survey	Entire Deck	Entire Deck	Recommended
	Half Cell Potential	5' x 5' Grid	Entire Deck	Recommended
	Chloride ion profile	10 total or 4 per span for multi-span	Emphasize Shoulders	Recommended
	Depth of Cover	Entire Deck (GPR) or 1 Reading per 25 SF for Pachometer	Take Readings on a Grid	Recommended
Fair	Visual and Delamination Survey	Entire Deck	Entire Deck	Recommended
	Half Cell Potential	5' x 5' Grid	Entire Deck	Recommended
	Chloride ion profile	10 total or 4 per span for multi-span	Emphasize Shoulders	Required
	Depth of Cover	Entire Deck (GPR) or 1 Reading per 25 SF for Pachometer	Take Readings on a Grid	Required
	Visual assessment of deck bottom	Entire Deck	Entire Deck	Required
Poor	Chloride ion profile	10 total or 4 per span for multi-span	Emphasize Shoulders	Required
	Depth of Cover	Entire Deck (GPR) or 1 Reading/25 SF for Pachometer	Take Readings on a Grid	Required
	Visual assessment of deck bottom	Entire Deck	Entire Deck	Required
Any	Petrographic Analysis	4 Tests	Designer Decision	Required if ASR Suspected
	Compressive Strength	4 Tests	Designer Decision	Required Only if Soft Concrete or Live Load-Induced Distress are Evident

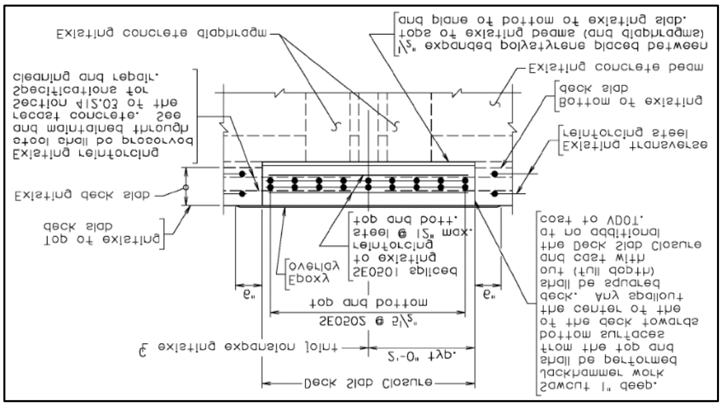

Fig. 6. *Flexible Link Slab with Epoxy Overlay Using A4 Modified Concrete Detail (concrete beam is shown)*

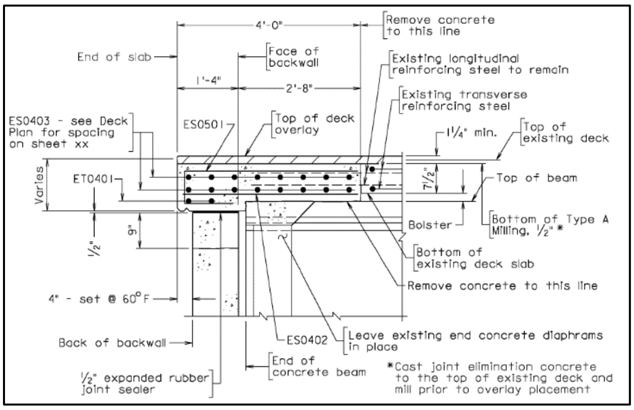

Fig. 7. *Deck Extension Detail (concrete beam is shown)*

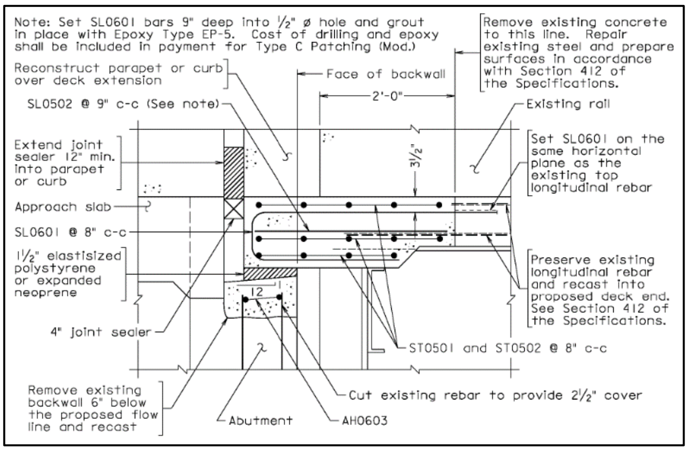

Fig. 8. *Micro Abutment Detail*

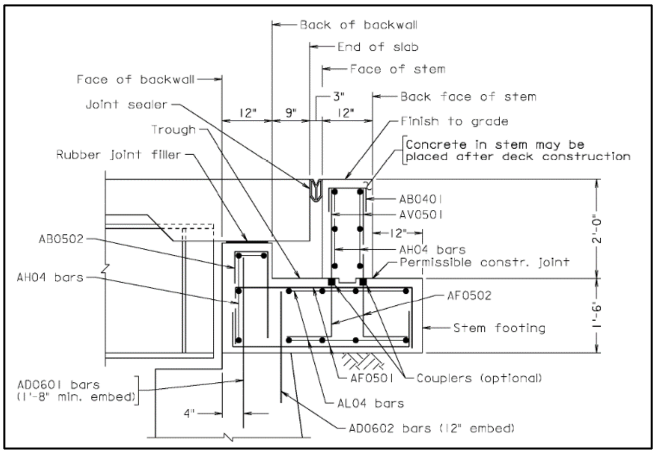

Fig. 9. *Alternate Virginia Micro-Abutment Detail*

8) Module (8): Bridge Rehabilitation

Rehabilitation involves major work required to restore a bridge's structural integrity and work necessary to correct major safety defects. Bridge rehabilitation projects provide comprehensive or nearly complete renovation of bridge elements or components. Restoration work can be done on one or multiple structure elements and/or components. Agencies may select to combine preservation activities on some elements while a component is being rehabilitated. Such projects require noteworthy engineering resources for the design, considerable costs, and a lengthy completion schedule. Examples of bridge rehabilitation contain, but are not limited to: complete or partial deck replacement, substructure/culvert strengthening or partial/full replacement, and superstructure replacement. Incidental widening is regularly associated with some of these activities.

The total replacement of an existing bridge with a new facility was constructed in the same general traffic corridor. The replacement structure must meet the current construction, geometric, and structural standards needed for the types and volume of the projected traffic on the facility during its design life. Replacement also includes a nominal amount of approach work, enough to connect the new facility to the current roadway or to return the grade line to a possible touchdown point.

9) Module (9): Pre-Measure

Inventory items pertain to a bridge's characteristics. Mostly, these items are permanent characteristics that only change when the bridge is altered in some way, such as bridge rehabilitation. So, inventory items should be replaced after rehabilitation and include the following NBI items:

- Identification – Identifies the structure using location codes and descriptions.
- Structure Type and Material – Categorizes the structure based on the material, design and construction, the number of spans, and wearing surface.
- Age and Service – Information showing when the structure was constructed or reconstructed, features the structure carries and crosses, and traffic information.
- Geometric Data – Includes pertinent structural dimensions.
- Design Load – The live load for which the structure was designed.
- Navigation Data – Identifies the existence of navigation control, pier protection, and waterway clearance measurements.
- Classification – Classification of the structure and the facility carried by the structure are identified.
- Required Inspections – Includes designated inspection frequency and critical features requiring special inspections or special emphasis during the inspection.

After rehabilitation, an inspection of the bridge components is typically performed. This inspection intends to compare the performance index before and after the rehabilitation. Several nondestructive techniques are used to inspect concrete bridge elements, including visual inspection, chain dragging, ground-penetrating radar, impact-echo testing, infrared thermography, and ultrasonic pulse velocity. Most agencies perform visual inspection and chain dragging as a minimum and supplement with more involved inspection techniques if needed. Tables XI and XII show the re-measuring performance of both Durability and Serviceability Data and Functionality, Cost, Structural Integrity, and Organizational Data.

10) Module (10): Final Assessment

Measures of accomplishment of rehabilitation actions are comparative. From these scenarios, the numbers and quantities of rehabilitation actions completed are compared to the numbers and quantities of actions planned. As a measure of rehabilitation, the average condition of bridge elements must be focused on bridges after rehabilitation. Calculating the added value to the bridge is usually required. A bridge preservation program consists of performing cost-effective cyclical and condition-based activities that seek to prolong the service life of bridges and delay the need for more rehabilitation or replacement. Owner agency steps to establish a preservation program are:

- Identify agency goals and objectives.
- Develop a list of actions for preservation.
- Establish rules for the actions, a combination of either cyclical or condition-based.
- Use the actions to develop life cycle plans.
- Develop performance measures for the effectiveness of the actions.
- Develop methods to evaluate the benefits of the actions.
- Dedicate funds for preservation actions.
- Monitor and measure the performance of the preservation program.
- Report and improve the preservation program.

IV. Research Findings

The outline of the model for retrofitting existing concrete structures can be summarized as follows:

- The model of the performance-based design was implemented.
- Steps forward in numerical analysis techniques and the evolution of precise simulation methods are powerful tools. It releases the uncertain sense of designers to the requirements of their structures, considering the required precision of the fundamental modeling and its construed parameters.
- The safety of an existing bridge is a matter of decision and science. Every statement about the safety of an existing bridge is subjective and reflects the state of knowledge of the team in charge of making the decision.

TABLE XI. RE-MEASURE OF DURABILITY AND SERVICEABILITY PERFORMANCE DATA

Category	Data
Design and construction	Design plans and specifications
	Critical design details
	Change orders
	Inspection notes
	Construction quality assurance and quality control
	Corrosion protection measures
Operating conditions	Local climate
	Snow and ice removal practices
	Freeze-thaw cycles
	Rainfall and runoff; drainage control
	Marine environment
	Industrial pollutants
Dynamic loadings	Traffic volume
	Truck volumes and weights
	Weigh-in-motion data
	Overload permits
	Debris, ice
	Impact loads
	Flexibility, vibrations
Corrosion protection measures	Concrete cover over reinforcement
	Corrosion resistant reinforcement
	Deck overlays, membranes, and sealers
	Other concrete sealers
	Steel coatings—high-performance or weathering steel
	Concrete qualities—high-performance concrete
Material conditions	Concrete
	Steel
	Reinforcing bars
	Prestressing steel
	Deck
	Concrete superstructure
	Steel superstructure
	Concrete substructure
Geometric data	Deflections
	Rotations
	Settlements
	Loss of camber
	Horizontal alignment and skew
Components	Bearings
	Joints
	Approach slabs
	Details requiring inspection by nondestructive evaluation

TABLE XII. RE-MEASURE OF FUNCTIONALITY, COST, STRUCTURAL INTEGRITY, AND ORGANIZATIONAL DATA

Categories		Data
Functionality: User safety and service	Operational efficiency	Traffic volumes
		Congestion and delay times
		Safety hazards
		Accident rates and types
	Network-level performance	Route redundancy
		Detour lengths and costs
		Other bridges in the corridor
	Environmental impacts	Fuel usage
		Air quality
	Environmental issues	Water quality
	Environmental impacts	Toxic wastes
	Original construction	Design costs
		Construction costs
	Life-cycle costs	Inspection and condition assessment
Costs: Agency and user	Original construction	Preservation
		Maintenance, repairs
	Life-cycle costs	Rehabilitation
		Demolition, removal, and disposal
		Work zone maintenance of traffic
	Safety and stability	Global
		Member
		Redistribution
Structural integrity: Safety and stability	Safety and stability	Resilience
		Structural redundancy
		Foundation type
	Extreme events	Accident risks—fire, impact
		Soil and hydraulic conditions
		Scour vulnerability
		Scour mitigation measures
		Seismicity
		Seismic design considerations
		Hazard return periods
Organizational issues		Organizational structure and culture
		Knowledge management
		Human resources
		Quality of education
		Incentives for growth

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