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Time-variant service reliability of post-tensioned, segmental, concrete bridges exposed to corrosive environments

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ABSTRACT

This paper presents a framework for assessing the service reliability of post-tensioned (PT) bridges with damaged and undamaged tendons containing voids, chlorides, and moisture. The service reliability is defined based on the probability that the normal stress due to the applied loads (i.e., demand) at the midspan of the girder attains or exceeds the corresponding allowable normal stress (i.e., capacity). The probabilistic model to determine the normal stress demand is formulated using statistical characteristics of highway traffic and bridge design loads, probabilistic models for the tension capacity of corroding strands, the AASHTO LRFD stress model for strands, and Todeschini's nonlinear stress model for concrete. The probabilistic model for capacity is based on the AASHTO LRFD normal stress limits. Using the developed reliability framework and Monte Carlo simulation, the time-variant service reliability of a typical PT bridge over a 75-year period is estimated. After chloride and moisture infiltrate the tendons, the service reliability reduces to a value below recommended values within a relatively short period of time.

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1. Introduction

The presence of chlorides, moisture, damage, and voids has been observed in tendon systems in segmental post-tensioned (PT) bridges. These conditions can lead to accelerated corrosion of strands resulting in tendon failure. For example, the Niles Channel, Mid-bay, and Bob Graham Sunshine Skyway bridges in Florida, and the Varina-Enon bridge in Virginia experienced tendon failures [1–4]. These incidents raise concern over the safety and serviceability of PT bridges exposed to corrosive environments.

The generalized reliability index, β can be considered as a quantitative measure for the safety (if the strength limit state is considered) or serviceability (if the service limit state is considered) of structural systems. In general, the term β can be defined based on the probability of the occurrence of failures (strength or service failure). To ensure good safety or serviceability, the value of β corresponding to a chosen limit state must be greater than a minimum required value, defined as the target reliability index, β_{target}. To ensure acceptable levels of safety, the load and resistance factors for the strength limit states in the American Association of State Highway and Transportation Officials, Load Resistance Factor Design (AASHTO LRFD) Specifications [5] are calibrated for a β_{target}, of 3.5 [6]. However, the load and resistance factors for the service limit states in AASHTO LRFD Specifications [5] are not yet calibrated for a specific β_{target}. Based on a comparative study on the reliability of concrete girders assessed using the AASHTO LRFD Specifications [7], Chinese code [8], and Hong Kong code [9], Du and Au [10] recommended to calibrate the bridge design codes for service limit states, to ensure a high level of serviceability. At present, the National Cooperative Highway Research Program (NCHRP) is conducting an unpublished study [11] on the calibration of the AASHTO LRFD Specifications for service limit states.

Researchers have suggested various β_{target} values to improve service reliability. A β_{target} value between 1.6 and 2.0 has been suggested for structural steel members [12]. A β_{target} value of 2.0 has been suggested for timber beams [13,14] and reinforced concrete beams [15]. The above discussion indicates that the typical β_{target} value for service failure is smaller than that for strength failure. This is because the consequences of service failure (e.g. tendon failure) are more affordable than the consequences of

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Nomenclature

β	Reliability index
β_{target}	Target reliability index
$\beta(\mathbf{x}, t)$	Time-variant reliability index
Δf_{pLT}	Prestress loss due to long term effects
ε	Standard normal random variable, $\sim$N(0, 1)
ϕ	Curvature at midspan of the girder
ϕ_{wet}	Wet-time (in months) in a year divided by 12
γ_{load}	Load factor
ρ_{box}	Unit weight of concrete in box section
$\rho_{\text{non-box}}$	Unit weight of concrete in overlay, wearing surface, and side barriers
θ_i	Unknown model parameter
σ	Standard deviation of model error
$A_{\text{as-received}}$	Cross-sectional area of as-received strand
A_c	Area of the concrete cross section
c	Depth of neutral axis at midspan of the girder
c_b	Distance from centroid of concrete cross-section to extreme bottom fiber
c_t	Distance from centroid of concrete cross-section to extreme top fiber
CG	Center of gravity
C_M	Moment capacity
C_f	Stress capacity
$C_{\text{compression},1}$	Allowable compressive stress at top fiber due to dead load only
$C_{\text{compression},2}$	Allowable compressive stress at top fiber due to dead and live loads
C_{tension}	Allowable compressive stress at top fiber due to dead and live loads
COV	Coefficient of Variation
C_T	Tension capacity
$C_{T,\text{as-received}}$	Tension capacity of as-received strand
DL_{box}	Dead load due to precast concrete box section
$DL_{\text{non-box}}$	Dead load due to concrete overlay, wearing surface, and side barriers
D_M	Moment demand
$D_{M,DL}$	Moment demand due to dead load only
$D_{M,LL}$	Moment demand due to live and impact loads
D_f	Stress capacity
$D_{\text{compression},1}$	Applied compressive stress at top fiber due to dead load only
$D_{\text{compression},2}$	Applied compressive stress at top fiber due to dead and live loads
D_{tension}	Applied compressive stress at top fiber due to dead and live loads
e_j	Eccentricity of jth strand from the centroid of concrete cross section
E_c	Elastic modulus of concrete
f_c	Normal compressive stress in concrete
f'_c	Actual compressive strength of concrete
$f'_{c,\text{specified}}$	Specified compressive strength of concrete
f_{pe}	Effective prestress in strand
f_{pi}	Initial prestress after anchoring
f_{ps}	Total stress in prestressing strand
f_{py}	Yield strength of prestressing strand
f_{pu}	Ultimate tensile strength of strand
F	Normal force in concrete
F_C	Normal compressive force
F_T	Normal tensile force
$g(\mathbf{x}, t)$	Service limit state function
$h_{t_{CA}}$	$\frac{\text{Total atmospheric exposure time (years)}}{\text{standardizing factor}} = \frac{t_{CA}}{0.75}$
n_{CA}	Constant based on field information $= -0.005$
h_T	Ambient exposure temperature (°F) $= T$ (°F)
h_{RH}	$\frac{\text{Ambient relative humidity (\%)}}{\text{Maximum Relative humidity (\%)}} = \frac{RH\ (\%)}{100}$
$h_{\%gCl^-}$	$\frac{\%Cl^- \text{ in the grout (by weight)}}{\%sCl^-_{\text{saturated chloride solution}}} = \frac{\%gCl^-}{35.7}$
$h_{\%sCl^-}$	$\frac{\%Cl^- \text{ in the water inside the tendon}}{\%sCl^-_{\text{saturated chloride solution}}} = \frac{\%sCl^-}{35.7}$
$h_{t_{WD}}$	$\phi_{\text{wet}} \times$ Total exposure time (years) $= \phi_{\text{wet}} \times t_{WD}$
j	Subscript j indicates jth strand
k	Moment arm
l_e	Effective tendon length (inches)
l_i	Length of the strand between anchorages (inches)
LL_{lane}	Live load based on lane load
LL_{tandem}	Live load based on tandem load
LL_{truck}	Live load based on truck load
M	Bending moment
MUTS	Minimum ultimate tensile strength
N_s	Number of support hinges crossed by the strand between the anchorages
N_{strands}	Total number of strands in the cross section
P_f	Probability of service failure
$P_{f,\text{target}}$	Target probability of service failure
$P_{\text{loss,as-received}}$	Prestress loss in as-received strands
PT	Post-tensioned
r	Radius of gyration
RH	Relative Humidity
S^t	Section modulus of concrete section w.r.t. the extreme top fiber
S_b	Section modulus of concrete section w.r.t. the extreme bottom fiber
T	Temperature
t	Exposure time or age of bridge
$\mathbf{x}$	Vector of influential parameters and variables
WDT	Number of tendons with wet–dry exposure

a strength failure (e.g., bridge collapse). The designation 13822, *Bases for design of structures — Assessment of existing structures* by the International Organization of Standardization (ISO 2001) recommends β_{target} values of 0 and 1.5 for service failures with reversible and irreversible consequences of failures, respectively.

The reliability of a structural system can reduce as a function of exposure conditions and time. Pillai et al. [16] developed a framework to assess the time-variant strength or flexural reliability (i.e., a safety performance indicator) of PT bridges exposed to corrosive environments. A framework to assess the time-variant service reliability is needed to assess the serviceability issues of PT bridges exposed to corrosive environments. These serviceability issues include concrete cracking, inelastic concrete compression, and strand/tendon failure due to corrosion and/or excessive normal stresses.

A general basis for the definition of β was provided earlier in this paper. Herein, the term β is defined based on the probability that the normal stress due to the applied loads (i.e., normal stress demand, D_f) at the midspan of the girder attains or exceeds the corresponding allowable normal stress (i.e., normal stress capacity, C_f). Based on structural reliability techniques and probabilistic models for D_f and C_f, this paper develops a framework to assess the time-variant service reliability index, $\beta(\mathbf{x}, t)$, of PT bridges. The vector $\mathbf{x}$ indicates the set of parameters and random variables (i.e., the tension capacity (denoted as C_T) of strands, the void condition, damage condition, environmental condition of tendons, and the external loading conditions and geometrical, material, and structural characteristics of the bridge) influencing D_f and C_f. The term t indicates the exposure time. Herein, 'service reliability' is simply denoted as 'reliability'.

The remaining paper is organized as follows. First, a review on corrosion and applied normal stresses in PT bridges is provided.

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