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Statistical Techniques for Assessment of Existing Concrete Structures—Report

Reported by ACI Innovation Task Group 11

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This report demonstrates how statistical techniques can be used in the assessment of concrete structures to evaluate their condition and reliability and to assess the relative merits of possible repair options. A Reliability Toolkit provides licensed design professionals with a summary of some statistical methods that are useful for structural assessment. The report also gives two detailed examples of assessments for structural concrete repair.

Keywords: confidence level; data analysis; durability; material properties; mean load method; rehabilitation; reliability; sample size; testing.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Licensed design professionals working with existing structures are often challenged with developing an appropriate scope of proposed work during an assessment or investigation phase to characterize the as-built and current conditions of a structure. While there are statistical techniques that can be used to establish appropriate sample sizes, in general, there is no "one-size-fits-all" approach to assessing structural condition. Performance-based standards for assessment, repair, and rehabilitation of existing concrete structures, such as ACI CODE-562, require methods for representative measurement of such performance. As an example, ACI CODE-562 uses statistical techniques for determining equivalent specified concrete compressive strength f_{ceq} for the strength assessment of existing structures. For other measurements needed for durability and structural assessments, testing and field investigation techniques are extensively documented but there is little guidance on adoption of statistical methods to reliably characterize the necessary parameters. Information on the use of statistical methods for assessment and repair of existing concrete structures is needed because the conventional, well-known methods used in manufacturing industries for quality assurance are often not practical for single, existing structures.

This report demonstrates how statistical techniques can be used to assess the performance of existing concrete structures and of proposed repairs. A Reliability Toolkit, included as Appendix A, provides licensed design professionals with a summary of some statistical methods that are useful for structural assessment. The report also gives two detailed examples of assessments for structural concrete repair. The first example assesses durability, while the second evaluates strength. Each illustrates how methods from the Toolkit are used to quantify field-measured data to a level of confidence determined by the licensed design professional.

Developing an adequate assessment is important in terms of technical effectiveness and cost efficiency. Chapter 3 provides guidance on which parameters should be quantified by testing, and Chapter 4 discusses sample sizes and the statistical analysis of test results. The durability example presented in Chapter 5 uses statistical analysis of cover and carbonation depth measurements to derive probable end-of-service-life limits. The strength example in Chapter 6 illustrates structural assessment using preliminary, detailed, and reliability-based techniques specified in ACI CODE-562. The Reliability Toolkit in Appendix A may become the most frequently used part of this document as users become familiar with reliability-based methods.

The toolkit and examples include applications of functions available in the Microsoft Excel software; similar functions are available in other software packages and these example applications should not be viewed as an endorsement of a particular software package.

1.2—Scope

The scope of this report is limited to providing a summary of statistical techniques that are applicable to the assessment of existing concrete structures and to providing two detailed examples of such applications. Further, an introduction to reliability computations is presented as a Reliability Toolkit. The report is not intended to present all statistical methods or reliability concepts applicable to concrete design, construction, and quality assurance applications. Instead, it is a succinct primer targeted to practitioners who are familiar with basic statistical principles, including data analysis, and who wish to expand their assessment techniques to include reliability-based statistical methods.

CHAPTER 2—NOTATION

A = observed value in Bayesian analysis
A_s = area of tension reinforcement, in.^{2}
A_s' = area of compression reinforcement, in.^{2}
A_v = area of shear reinforcement, in.^{2}
a = depth of equivalent rectangular concrete stress block, in.

a, b = constants in sum of independent random variables
B_i = set of all possible states of unknown parameter in Bayesian analysis, including B_j
B_j = particular state of unknown parameter in Bayesian analysis
b = effective width of cross section, in.
b_w = web width, in.
C_m = approximate moment coefficient for structural analysis
c = clear concrete cover (individual measurement c_i; mean $\overline{c}$; standard deviation s_c), in.
c, d = constants in product of independent random variables
$(\overline{c})_x$ = estimate of confidence mean cover at x confidence level, in.
D = dead load effect (mean $\overline{D}$; bias coefficient δ_D; coefficient of variation V_D)
d = effective depth of reinforcement (mean value $\overline{d}$; coefficient of variation V_d), in.
d_b = bar diameter, in.
d_c = depth of carbonation (mean $\overline{d_c}$; standard deviation s_d), in.
E = target allowable error, expressed as a fraction (or percentage) of the mean value
e = target allowable error
$F(x_i)$ = sample cumulative distribution function (CDF) value for data point x_i
$F_{X_A}(x_A)$ = CDF of annual maximum extreme value distribution for data point x_A
$F_{X_N}(x_N)$ = CDF of N-year maximum extreme value distribution for data point x_N
$F_X^e(x)$ = CDF of event distribution
$F_X^m(x)$ = CDF of extreme value distribution
$f_{0.10}$ = lower 10% fractile value of a quantity
f, g = arbitrary functions
f_c' = concrete compressive strength (mean value $\overline{f_c'}$; coefficient of variation $V_{fc'}$), psi
f_{ceq} = equivalent-to-specified concrete compressive strength, psi
f_y = reinforcement yield stress (mean value $\overline{f_y}$), psi
f_{yeq} = equivalent-to-specified reinforcement yield stress, psi
f_{yt} = transverse reinforcement yield stress, psi
f_{yteq} = equivalent-to-specified transverse reinforcement yield stress, psi
g_i = standard Gumbel variate for data point x_i
h = overall height of rectangular or circular member, in.
h_p = height of beam stem projection beneath slab soffit, in.
h_s = slab thickness, in.
k = carbonation rate constant
$k_{0.10}$ = one-sided tolerance factor for 10% fractile
k_c, k_s = coefficient of variation modification factors specified in ACI CODE-562
L = live load effect (mean $\overline{L}$; bias coefficient δ_L; coefficient of variation V_L)
ℓ_n = clear span length, in.
M = bending moment, ft-kip
M_A, M_{AB}, M_B = moments at support section A, span section AB, and support section B, respectively, ft-kip
M_D = dead load moment (mean $\overline{M_D}$; standard deviation σ_D), ft-kip
M_L = live load moment (mean $\overline{M_L}$; standard deviation σ_L), ft-kip
M_n = nominal bending moment capacity, ft-kip
M_u = factored applied moment, ft-kip
N = number of events that occur in a specific time interval
n = sample size, number of independent random variables in Taylor Series Linearization
P = probability; professional factor, ratio of test to predicted value (mean value $\overline{P}$; bias coefficient δ_P; coefficient of variation V_P)
R = resistance (mean $\overline{R}$; standard deviation s_R; coefficient of variation V_R)
R^2 = coefficient of determination in regression analysis
r_i = rank of data point x_i
S = load effect or demand (mean load effect $\overline{S}$; standard deviation σ_S; coefficient of variation V_S)
s = sample standard deviation computed for a dataset; stirrup spacing, in.
s^2 = sample variance computed for a dataset
s_A = standard deviation of annual maximum extreme value distribution
T = return period, years
$T_{P,n-1}$ = Student's t-distribution with n-1 degrees of freedom at Confidence Level P
t_y = time, years
V = coefficient of variation, standard deviation divided by the mean
V_c = shear resistance provided by concrete, kip
V_{core} = coefficient of variation of core strengths
V_n = nominal shear resistance, kip
V_u = factored shear demand, kip
v = wind speed (individual data point v_i; mean $\overline{v}$)
w = uniformly distributed load, lb/ft; lb/ft^2
w_i = truck weight data point (mean value $\overline{w_e}$; standard deviation s_e)
w_L = uniformly distributed load due to live load, lb/ft, lb/ft^2
w_{SDL} = uniformly distributed load due to superimposed dead load, lb/ft; lb/ft^2
w_{SW} = uniformly distributed load due to self-weight, lb/ft; lb/ft^2
w_u = factored uniformly distributed load, lb/ft; lb/ft^2
X_i = independent random variable (mean value $\overline{X_i}$; standard deviation σ_{X_i}; variance, $\sigma_{X_i}^2$; coefficient of variation V_{X_i})