

# Statistical Techniques for Assessment of Existing Concrete Structures—Report

Reported by ACI Innovation Task Group 11

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## **Statistical Techniques for Assessment of Existing Concrete Structures—Report**

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# Statistical Techniques for Assessment of Existing Concrete Structures—Report

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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.

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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 exten-

sively 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.<sup>2</sup>
- $A_s'$  = area of compression reinforcement, in.<sup>2</sup>
- $A_v$  = area of shear reinforcement, in.<sup>2</sup>
- $a$  = depth of equivalent rectangular concrete stress block, in.

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