The new generation of load and resistance factor design (LRFD) codes is based on probabilistic methods. Structural performance depends on the uncertainty involved in the applied load and in the load-carrying capacity. Therefore, the load and resistance factors represent partial safety factors and their values are a function of bias factors (ratios of mean to nominal) and coefficients of variation.\textsuperscript{1,2}

The primary load combination for highway bridges includes dead load, live load, and dynamic load. Each of the individual components is random in nature. Moreover, the live-load effect also depends on truck position on the bridge and load distribution factor. The statistical parameters of live load are taken from the recent study presented by Rakoczy\textsuperscript{3} and Nowak et al.\textsuperscript{4} based on an extensive weigh-in-motion survey.

The uncertainty in the resistance model is caused by variability in material properties, dimensions, and analytical procedures. Each parameter can be considered as a random variable and can be described by statistical parameters such as the mean value $\mu$, standard deviation $\sigma$, coefficient of variation $V$, probability density function, and cumulative distribution function (CDF). Assessing the statistical parameters requires extensive material and component testing. However, because of the prohibitive cost, full-scale
tests are limited or impossible. Therefore, the behavior of large bridge components must be evaluated using analytical methods and simulations.

The objective of this study is to calculate the reliability indices for prestressed concrete girders using new statistical parameters for material and load components. The sensitivity analysis was performed and the results presented for resistance and load parameters that can affect reliability indices of prestressed concrete beams. The analysis is presented for American Association of State Highway and Transportation (AASHTO) type girders and Nebraska University (NU) girders.6,7

**Research significance**

Prestressed, precast concrete beams are widely used in highway multigirder bridges because of lower construction costs and increased span length. Recently, new and updated statistical parameters are available for material properties and live load on highway bridges. Therefore, there is a need to evaluate the performance of prestressed concrete beams based on new load and resistance models. The sensitivity analysis performed establishes a relationship between resistance and load parameters and reliability index and thus helps to identify the most critical parameters for prestressed concrete beams. The results of this study can serve as a basis for verification of the current design code provisions, including review of load and resistance factors.

**Statistical parameters of material**

The statistical parameters of the material factor for tensile strength of prestressing strands were developed based on new data that include 47,421 samples of strands of 0.5 in. (13 mm) and 0.6 in. (15 mm) diameter. The data were obtained from five U.S. fabricators.

For a more efficient interpretation, the statistical data were plotted on normal probability paper. The properties and use of normal probability paper can be found in textbooks on statistics and probability theory, for example, Nowak and Collins.8 The most valuable characteristic of probability paper is easy evaluation of the statistical parameters as well as type of the distribution function. The vertical axis on normal probability paper is the inverse of the standard cumulative distribution and represents the number of standard deviations from the mean value. If the CDF curve is close to a straight line, then the considered variable has a normal distribution. In this case, the mean value and standard deviation can be read directly from the CDF plot. Bias factor $\lambda$ is defined as the ratio of the mean to nominal value, and the coefficient of variation is calculated as a standard deviation divided by the mean.1,2

First, the CDF of the ultimate strength of prestressing strands is plotted on normal probability paper. The CDFs of tensile strength of prestressing strands of 0.5 and 0.6 in. (13 and 15 mm) diameters are close to a straight line (Fig. 1 and 2). This is more visible when all of the data points are plotted together.

The statistical parameters such as mean value $\mu$, bias factor $\lambda$, and coefficient of variation $V$ can be determined directly from the graph representing the CDF. Table 1 summarizes the statistical parameters for prestressing strands.

The statistical parameters for ordinary concrete were obtained by Nowak et al.,9 including the test data of 28-day

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Figure 1. Cumulative density functions of tensile strength of 0.5 in. diameter prestressing strands. Source: Reproduced from Nowak and Rakoczy (2012). Note: $f_u =$ ultimate strength of reinforcing steel. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.
compressive strength of concrete for standard cylinders, 6 in. x 12 in. (150 mm x 300 mm), ordinary concrete with nominal compressive strength $f'_c$ of 3000 to 6500 psi (21 to 45 MPa), and high-strength concrete with nominal compressive strength $f'_c$ of 7000 to 12,000 psi (49 to 84 MPa).

The CDFs for each nominal compressive strength $f'_c$ from 3000 to 12,000 psi (21 to 84 MPa) were plotted on normal probability paper (Fig. 3). Table 2 lists the recommended bias factor $\lambda$ and coefficients of variation $V$ of compressive strength $f'_c$. The statistical parameters are given separately.

**Table 1. Summary of the statistical parameters for prestressing**

<table>
<thead>
<tr>
<th>Strand diameter, in.</th>
<th>Number of samples</th>
<th>Bias factor $\lambda$</th>
<th>Coefficient of variation $V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>33,387</td>
<td>1.04</td>
<td>0.017</td>
</tr>
<tr>
<td>0.6</td>
<td>14,028</td>
<td>1.02</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Source: Reproduced from Nowak and Rakoczy (2012). Note: 1 in. = 25.4 mm.
The resistance of a structural component $R$ is a random variable related to uncertainties resulting from material properties and dimensions. It is convenient to consider $R$ as a product of nominal value $R_n$, material factor $M$, fabrication factor $F$, and professional factor $P$ as is expressed in Eq. (1).

$$R = R_n M F P$$  \(1\)

The nominal capacity of prestressed concrete girders was determined according to AASHTO LRFD Bridge Design Specification provisions for flexure. The formula for bend-
ing moment Eq. (2) is based on AASHTO LRFD specifications (Eq. [5.7.3.2.2-1]) provisions.

\[
M_n = A_{ps}f_{ps}\left(d_r - \frac{a}{2}\right) + A_s f_s\left(d_c - \frac{a}{2}\right) - A_{ps} f_{ps}\left(d_p - \frac{a}{2}\right) + 0.85 f_{ps} (b - b_w) h_f \left(\frac{a - h_f}{2}\right)
\]

where

\[
\begin{align*}
A_{ps} &= \text{area of prestressing steel} \\
f_{ps} &= \text{average stress in prestressing steel at nominal bending resistance} \\
d_r &= \text{distance from extreme compression fiber to centroid of prestressing tendons} \\
a &= \text{depth of the equivalent stress block} = c\beta_i \\
c &= \text{distance from extreme compression fiber to neutral axis} \\
\beta_i &= \text{stress block factor} \\
A_s &= \text{area of mild steel tensile reinforcement} \\
f_s &= \text{stress in mild steel tensile reinforcement at nominal flexural resistance} \\
d_c &= \text{distance from extreme compression fiber to centroid of mild steel tensile reinforcement} \\
A'_s &= \text{area of mild steel compressive reinforcement} \\
f'_s &= \text{stress in mild steel compressive reinforcement at nominal flexural resistance} \\
d'_s &= \text{distance from extreme compressive fiber to centroid of mild steel compressive reinforcement} \\
b &= \text{width of compression face of member; for a flange section in compression, effective width of flange} \\
b_w &= \text{web width or diameter of a circular section} \\
h_f &= \text{compression flange depth of an I or T member}
\end{align*}
\]

The new material test data, described in the previous section, served as a basis for material factor \( M \). It was observed that statistical parameters for material improved over the years.

Variation in dimensions and geometry is represented by fabrication factor \( F \). No new data are available for the fabrication factor; therefore, the recommended statistical parameters were based on previous studies by Ellingwood et al.\(^{11}\) For the dimensions of cast-in-place concrete components, the recommended parameters of the \( F \) coefficient of variation \( V_F \) are 0.92 and 0.12, respectively, for effective depth of slab and \( \lambda_F \) of 1.01 and \( V_F \) of 0.04 for effective width of beam. For effective depth of prestressed concrete girder, \( \lambda_F \) of 1.0 and \( V_F \) of 0.025 are recommended.

For steel components, reinforcing bars, and stirrups, the statistical parameters are \( \lambda_F \) of 1.0 and \( V_F \) of 0.01. The area of reinforcing steel \( A_s \) is treated as a practically deterministic value, with \( \lambda_F \) of 1.0 and \( V_F \) of 0.015; similarly, the area of prestressing strands has a \( \lambda_F \) of 1.0 and \( V_F \) of 0.01.

The professional (analysis) factor \( P \) represents the variation in the ratio between the actual resistance and what can be analytically predicted using accurate material strength and dimension values. The professional factor’s bias factor \( \lambda_P \) and coefficient of variation \( V_P \) for a prestressed concrete beam in flexure are 1.01 and 0.06, respectively. Those statistical parameters of \( P \) are based on the study by Ellingwood et al.\(^{11}\)

In this study, the statistical parameters of resistance were taken from previous research.\(^{12}\) Nominal capacity was calculated according to AASHTO LRFD specifications. Then, each of the design parameters, which were treated as random variables, was simulated 1 million times using the Monte Carlo technique, and then values of resistance were calculated accordingly. The resulting CDFs were plotted on normal probability paper. The mean resistance \( \mu_R \), standard deviation of resistance \( \sigma_R \), bias factor of resistance \( \lambda_R \), and coefficient of variation of resistance \( V_R \) were calculated using CDF plots. The analysis was performed for the NU girders and AASHTO girders with different span lengths, different spacing between the beams, and two types of concrete: \( f_{ps} \) of 10,000 psi (69 MPa) for prestressed concrete girders and \( f_{ps} \) of 5000 psi (34 MPa) for the concrete slab. Statistical parameters of resistance were about the same for all types of girders. Statistical parameters of flexural resistance for prestressed concrete beams depended only on the strand diameter. The bias factor for resistance was 1.05 for strands of 0.6 in. (13 mm) diameter and 1.07 for strands of 0.5 in. (15 mm) diameter. The coefficient of variation for both cases was low, about 0.07. The bias factor for shear resistance for prestressed concrete beams was 1.20 and coefficient of variation was 0.115 regardless of the size of the strands. More detailed information about the statistical parameters is provided by Nowak and Rakocy.\(^{12}\)

**Load and load combination models**

The main load components for short- and medium-span highway bridges are dead load, live load, and dynamic
load. Environmental conditions (wind, ice, and temperature) and extreme events (collisions) may have additional load effects. In this study only primary load components were considered.

Dead load is the permanent weight of structural and non-structural members of a bridge. It is convenient to separate precast concrete elements, cast-in-place components (slab), and wearing surface (concrete or asphalt). In this study, the bias factor $\lambda$ value of cast-in-place members is 1.05 and coefficient of variation $V$ is 0.10, whereas for precast concrete components, bias factor $\lambda$ is 1.03 and coefficient of variation $V$ is 0.08. For wearing surface, $\lambda$ is 1.00 and coefficient of variation $V$ is 0.25. The statistical parameters for dead load were taken from the literature. 2,11

The most recent live-load model was developed by Rakoczy 3 and Nowak et al. 4 based on an extensive weigh-in-motion survey including more than 65 million vehicles at 32 different locations. Table 3 lists the statistical parameters. The values for 90, 120, and 200 ft (27, 36, and 61 m) were taken from research by Rakoczy 3 and Nowak et al. 4 For other span lengths, the results were linearly interpolated or extrapolated.

The parameters were derived for static load only. In the total load model, the dynamic load had to be included, and it was taken as 0.1 of the static load. The coefficient of variation $V$ of total live load is 0.18 for all span length, as recommended in National Cooperative Highway Research Program report 368. 2

The statistical parameters of the total load also depend on the dead load–to–live load ratio. For longer bridges, dead load can be larger than live load, and for short-span bridges, they can be about the same. Therefore, the reliability analysis was performed for span lengths ranging from 80 to 200 ft (24 to 61 m).

In the AASHTO LRFD specifications, the design load HL-93 is either a three-axle design truck and uniform load equal to 0.64 kip/ft (9.3 kN/m) or a design tandem with two axles of 25 kip (110 kN) spaced at 4 ft (1.2 m) and a uniform load of 0.64 kip/ft (9.34 kN/m). The load case that produces the greater load effect governs.

The design loads are multiplied by load factors to obtain a factored total design load $Q_d$ as is presented in Eq. (3).

$$Q_d = 1.75(LL + IM) + 1.25DC + 1.5DW$$

where

$DC$ = dead load of structural components and nonstructural attachments

$DW$ = dead load of wearing surface and utilities

$LL$ = vehicular live load

$IM$ = vehicular dynamic load allowance

<table>
<thead>
<tr>
<th>Span, ft</th>
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<th>ADTT 5000</th>
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<td>1.42</td>
<td>1.43</td>
<td>1.45</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Source: Data from Rakoczy (2011). Note: ADTT = average daily truck traffic; $\lambda_{LL}$ = bias factor of live load. 1 ft = 0.305 m.
Moreover, the reliability index $\beta$ is related to the probability of failure (Eq. [6]).

$$\beta = -\Phi^{-1}(P_f)$$  \hspace{1cm} (6)

where

$\Phi = \text{standard normal distributions function}$

The reliability index for a limit state function defined in Eq. (4) can be calculated using the general formula Eq. (7).  

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$  \hspace{1cm} (7)

where

$\mu_Q = \text{mean load effect}$

$\sigma_Q = \text{standard deviation of load effect}$

One of the first steps in the reliability procedure is to define the limit state function for the considered structural type. In this study, the flexural limit state of prestressed concrete girders was considered. The reliability index was calculated for various average daily truck traffic values from 250 to 10,000 and for span lengths from 80 to 200 ft (24 to 61 m). For each considered span length and girder spacing, dead load and live load were estimated and treated as constants. The design of prestressed concrete girders was according to AASHTO LRFD specifications. Then the statistical parameters of load, mean load effect $\mu_Q$, and coefficient of variation for load effect $V_Q$ were calculated using the load model parameters.
Figure 5 plots the results of the reliability analysis for bending moment with a resistance factor $\phi$ of 1.0 versus span length. The results show that $\beta$ is about 3.6 for lower average daily truck traffic and 3.4 for higher average daily truck traffic. Also, shorter bridges have a slightly higher $\beta$ than longer span bridges.

**Sensitivity analysis**

The performance of the structure can be underestimated or overestimated because of insufficient data, time-related changes, or human error. Some parameters have a major effect on overall performance, while others do not. The important parameters can be identified by sensitivity analysis. Therefore, sensitivity analysis was conducted for typical prestressed, precast concrete girders. The considered load, resistance, and section geometry parameters were dead load $DL$ (sum of $DC$ and $DW$), live load $LL$, dynamic load allowance $IM$, material strengths $f_{ps}$ and $f_{poo}$, effective depth $d$, width of the compression face of the member $b$, and area of prestressing steel $A_{ps}$.

Load components were treated as separate parameters and were increased one at a time by 10% from the nominal value. Resistance parameters were grouped in three subgroups: $f_{ps}A_{ps}$, $b$, $f_{poo}$, and $d$. To check the sensitivity of resistance parameters, the reliability indices were calculated for their nominal values and then for resistance parameters reduced by multiples of 10%.

The reliability indices were calculated for the AASHTO and NU concrete girders with spans from 100 to 200 ft (30 to 61 m). Figures 6 and 7 show the drop of the reliability index for reduced/increased load and resistance parameters for all of the considered girders. The vertical axis is the ratio of the reliability index corresponding to either an increased load component or reduced resistance parameter and the reliability index for an intact girder.

The results indicate that reliability depends mostly on the strength $f_{ps}$, and cross-sectional area $A_{ps}$ of the prestressing steel and effective depth $d$. The reduction of effective depth by 30% to 35% reduced the reliability index to the negative values. The concrete strength $f_{c}$, effective width $b$, and dynamic load allowance $IM$ are not important.

The reliability of a girder depends mostly on the resistance parameters. Reduction of the critical parameters, that is, $f_{ps}$ and $A_{ps}$, reduces the reliability index (Fig. 8) for the considered types of girders. The vertical axis represents the ratio of the reliability index corresponding to reduced resistance parameter and the reliability index for an intact girder. The reliability index drops by 100% when prestressing steel $f_{ps}A_{ps}$ is reduced about 40%. Similarly, Fig. 8 shows the effect of a reduced effective depth $d$. This parameter is more important because, for example, a decrease of effective depth $d$ by 30% to 35% causes a 100% decrease in the reliability index.

**Conclusion**

The statistical parameters of resistance were considered for AASHTO and NU girders designed according to the AASHTO LRFD specifications. Based on a large material test data set for prestressing strands provided by the industry, new statistical parameters of resistance were derived. The results indicate that concrete and reinforcing steel properties have improved over the past 30 years, and this can have a positive effect on the load-carrying capacity of structural components.
the reliability is mostly affected by the prestressing steel \( f_{psAps} \) and effective depth \( d \). The reduction of effective depth by 30% to 35% caused a 100% decrease in the reliability index. Reliability indices drop 100% when prestressing steel \( f_{psAps} \) is reduced about 40%. The least important parameters are concrete strength \( b \) and dynamic load allowance \( IM \).

**References**


On the other hand, the new statistics for live load indicate that traffic volumes and truck weights have increased.\(^3\)\(^,\)\(^4\) Increased loading has a negative effect on the reliability index.

The reliability analysis was performed for AASHTO and NU prestressed, precast concrete girders with spans from 80 to 200 ft (24 to 61 m) and average daily truck traffic from 250 to 10,000 vehicles using the new statistics for resistance and load effect.

The sensitivity analysis was performed for typical prestressed concrete girders. The considered parameters included load components, material strength, and section geometry. The results of sensitivity analysis indicate that
Notation

\( a = \) depth of the equivalent stress block = \( c \beta_i \)

\( A_{ps} = \) area of prestressing steel

\( A_i = \) area of mild steel tensile reinforcement

\( A_c = \) area of mild steel compressive reinforcement

\( b = \) width of the compression face of the member; for a flange section in compression, the effective width of the flange

\( b_w = \) web width or diameter of a circular section

\( c = \) distance from extreme compression fiber to neutral axis

\( d = \) effective depth

\( d_p = \) distance from extreme compression fiber to the centroid of prestressing tendons

\( d_s = \) distance from extreme compression fiber to the centroid of mild steel tensile reinforcement

\( d'_c = \) distance from extreme compressive fiber to the centroid of mild steel compressive reinforcement

\( DC = \) dead load of structural components and nonstructural attachments

\( DL = \) total dead load (\( DC + DW \))

\( DW = \) dead load of wearing surfaces and utilities

\( f'_c = \) specified compressive strength of concrete at 28 days, unless another age is specified

\( f_{ps} = \) average stress in prestressing steel at nominal bending resistance

\( f_s = \) stress in mild steel tensile reinforcement at nominal flexural resistance

\( f'_c = \) stress in mild steel compressive reinforcement at nominal flexural resistance

\( f_u = \) ultimate strength of reinforcing steel

\( f_y = \) yield stress of reinforcing steel

\( F = \) fabrication factor
\( g \) = limit state function  \( \sigma_R \) = standard deviation of resistance

\( h_f \) = compression flange depth of an I or T member  \( \phi \) = resistance factors

\( IM \) = vehicular dynamic load allowance  \( \Phi \) = standard normal distribution function

\( LL \) = vehicular live load allowance

\( M \) = material factor

\( P \) = professional factor

\( P_f \) = the probability of failure

\( R \) = resistance (capacity)

\( R_n \) = nominal value

\( Q \) = load effect (demand)

\( Q_d \) = factored total design load

\( V \) = coefficient of variation

\( V_F \) = coefficient of variation for fabrication factor \( F \)

\( V_P \) = coefficient of variation for professional factor \( P \)

\( V_Q \) = coefficient of variation for load effect \( Q \)

\( V_R \) = coefficient of variation of resistance \( R \)

\( \beta \) = reliability index, defined as a function of the probability of failure

\( \beta_1 \) = stress block factor

\( \lambda \) = bias factor

\( \lambda_F \) = bias factor for fabrication factor \( F \)

\( \lambda_{LL} \) = bias factor of live load

\( \lambda_P \) = bias factor for professional factor \( P \)

\( \lambda_R \) = bias factor of resistance \( R \)

\( \mu \) = mean value

\( \mu_Q \) = mean load effect

\( \mu_R \) = mean resistance

\( \sigma \) = standard deviation

\( \sigma_Q \) = standard deviation of load effect
About the authors

Anna M. Rakoczy is a postdoctoral research assistant in the Department of Civil Engineering at the University of Nebraska–Lincoln. She received her PhD from UNL in 2012. Her major research area is structural engineering, and she has studied and worked in reliability and risk analysis, structural analysis, and design code calibration. Her research interests include the development of reliability-based design criteria for lightweight concrete structures and evaluation criteria for serviceability limit states of railway bridges.

Andrzej S. Nowak has been a professor of civil engineering at the University of Nebraska–Lincoln since 2005, after 25 years at the University of Michigan. He is a Fellow of ACI and member of ACI committees 343, Concrete Bridges and 348, Structural Safety. His major contribution is the development of reliability-based calibration procedure for limit state design codes. The procedure was successfully applied to the development of the AASHTO LRFD code and calibration of resistance factors for ACI 318.

Abstract

Structural performance of bridges depends on the applied loads and the load-carrying capacity, both of which are random in nature. Therefore, probabilistic methods are needed to quantify safety. It has been widely agreed to measure structural reliability in terms of a reliability index.

Material properties have changed over the last 30 years. The new material test data include compressive strength of concrete, yield strength of reinforcing steel, and tensile strength of prestressing strands. Average daily truck traffic and gross vehicle weight have also changed. The updated statistical parameters for prestressed concrete girders and live load affect the reliability indices.

The objective of this paper is to present the results of the reliability analysis for prestressed concrete girders using the most recent live load and resistance (flexure) models. Several types of American Association of State Highway and Transportation Officials girders and Nebraska University (NU) girders are considered with spans ranging from 80 to 200 ft (24 to 61 m) and girder spacings from 8 to 10 ft (2.4 to 3 m).

An important part of the research presented is derivation of sensitivity functions for various parameters that affect performance of prestressed concrete girders. The focus is on strength limit states, in particular bending capacity. The contribution of several resistance parameters, such as reinforcement area and yield stress, is considered. The procedure is demonstrated on representative girder bridges.

Keywords

Girder, load and resistance factor design, LRFD, reliability analysis, sensitivity analysis, statistical parameters, strand.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute’s peer-review process.

Reader comments

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