Reliability analyses of interface shear transfer in AASHTO LRFD specifications model and an alternative model

Mahmoodreza Soltani

- Previous research has shown that the interface-shear-transfer model of the *AASHTO LRFD Bridge Design Specifications* produces inconsistent levels of accuracy for different values of design variables.
- In this study, reliability analyses were performed on the AASHTO LRFD specifications model and an alternative model to evaluate and determine their resistance factors.
- The results of the reliability study showed that the alternative model performs better than the AASHTO LRFD specifications model.

Many reinforced concrete structures, such as bridges, depend on the transfer of shear forces across concrete-to-concrete interfaces where no or negligible moment is present. This phenomenon is explained by a theory called interface shear transfer (IST). One of the most common examples of IST occurs at the connection of precast concrete girders and cast-in-place concrete bridge decks (**Fig. 1**). Composite action between the girder and deck, which is aided by the interface transfer of shear forces, results in bridge stiffness and strength.

Soltani and Ross[1] created a database from 774 tests conducted between 1969 and 2014. This study showed that current code-based IST models produce inconsistent levels of accuracy for the ratio of experimental strength to nominal strength (bias factor) throughout the range of design variables. For example, bias factors in the IST model of the 2014 American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] were 1.49 and 1.85 (with and without resistance factor applied, respectively), and the model accuracy also varied significantly for different compressive strengths of concrete. Recognizing the limitations of the current AASHTO LRFD specifications–based IST design model, Soltani et al.[3] proposed a new IST design model developed through a multiple linear-regression analysis. Soltani et al.'s revised IST model produced more accurate results and a bias factor of 1.29 with consistent levels of accuracy throughout the considered range of design variables.

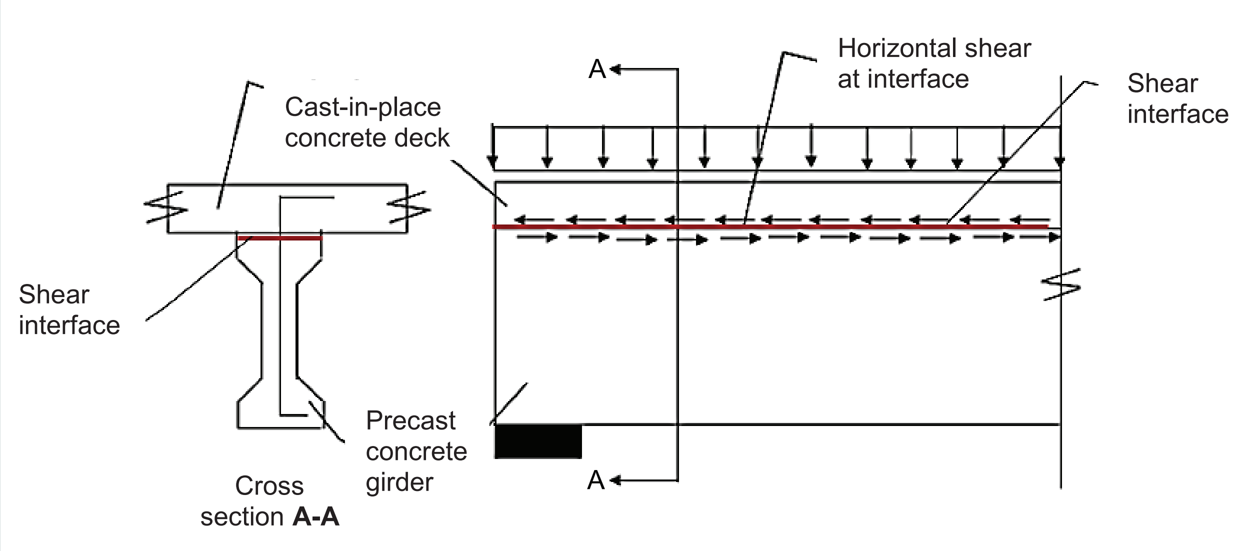


Figure 1. Graphic showing location of nterface shear transfer between precast concrete girder and cast-in-place concrete deck.

The objective of the present study is threefold. First, the reliability level of the 2014 AASHTO LRFD specifications–based model for predicting the nominal IST resistance is delineated based on the IST database created by Soltani and Ross.[1] This is achieved by defining the mean and coefficient of variation of resistance and the load distribution models. Second, a resistance factor is determined for Soltani et al.'s IST model to reach the 2014 AASHTO LRFD specifications reliability index target value of 3.50. Third, this study illustrates the reliability indices in different intervals throughout the range of all IST design variables, including interface area of concrete A_{cv}, interface shear reinforcement ρf_y, compressive strength of concrete f'_c, roughness amplitude of interface R, and compressive force normal to the shear plane P_c. These design variables are the main parameters that affect IST capacity, according to the sensitivity analysis performed by Soltani et al.[3]

Background

Interface shear transfer

Three mechanisms resist the shear forces passing through a concrete-to-concrete interface. These mechanisms are as follows:

- shear-friction[4,5]
- cohesion between concrete surfaces[6]
- dowel action of reinforcement[7,8]

Mast[4] and Birkeland and Birkeland[5] initially proposed the shear-friction mechanism to explain shear force transfer across cracks in reinforced concrete members. **Figure 2** illustrates the shear-friction mechanism using a sawtooth model.[7] Shear force parallel to the interface causes a horizontal displacement h between two concrete surfaces. The horizontal displacement is accompanied by a vertical displacement v due to concrete interlock. The vertical displacement causes tension in the steel reinforcement crossing the interface; this tension results in a clamping force and friction along the interface. Cohesion is the bond between concrete interface surfaces. Dowel action is due to the direct shear resistance of the reinforcement crossing the interface.

AASHTO LRFD specifications IST model

Section 5.8.4 of the 2014 AASHTO LRFD specifications contains the provisions for the IST model, with the factored interface shear resistance V_{ri} determined by Eq. (1).

$$V_{ri} = \phi V_{ni} \tag{1}$$

where

ϕ = shear resistance factor (0.90 for normalweight concrete and 0.80 for lightweight concrete)

V_{ni} = nominal interface shear resistance

In addition, the requirement in Eq. (2) must be fulfilled.

$$V_{ri} \geq V_{ui} \tag{2}$$

where

V_{ui} = factored interface shear force due to the total load based on the applicable strength and extreme-event load combinations

In the AASHTO LRFD specifications, the nominal capacity is calculated based on the summation of cohesion at the interface and friction that results from interface reinforcement and clamping force.

According to the IST provisions of the AASHTO LRFD specifications (Eq. 5.8.4.1-3), the nominal capacity can be found using Eq. (3).

$$V_{ni} = cA_{cv} + \mu(A_{vf}f_y + P_c) \tag{3}$$

where

c = cohesion factor

μ = friction factor

A_{vf} = area of interface shear reinforcement crossing the shear plane within the area A_{cv}

f_y = yield stress of reinforcement

In addition, the requirements in Eq. (4) and (5) must be fulfilled.

$$V_{ni} \le K_1 f'_c A_{cv} \tag{4}$$

$$V_{ni} \le K_2 A_{cv} \tag{5}$$

where

K_1 = fraction of concrete strength available to resist interface shear

K_2 = limiting interface shear resistance

The specified compressive strength must be greater than 16.55 MPa (2.400 ksi). **Table 1** gives the factors c, μ, K_1, and K_2 (AASHTO LRFD specifications section 5.8.4.3).

Soltani et al.'s revised IST model

Soltani et al.'s IST model is determined through the summation of three terms: cohesion, friction from interface reinforcement, and friction from compression force normal to the interface. The predicted IST strength V_{pre} is given by Eq. (6).

$$V_{pre} = CA_{cv} + M_1 A_{vf} f_y + M_2 P_c \tag{6}$$

where

C = cohesion coefficient

M_1 = friction coefficient for the shear-friction mechanism

M_2 = friction coefficient for the normal force

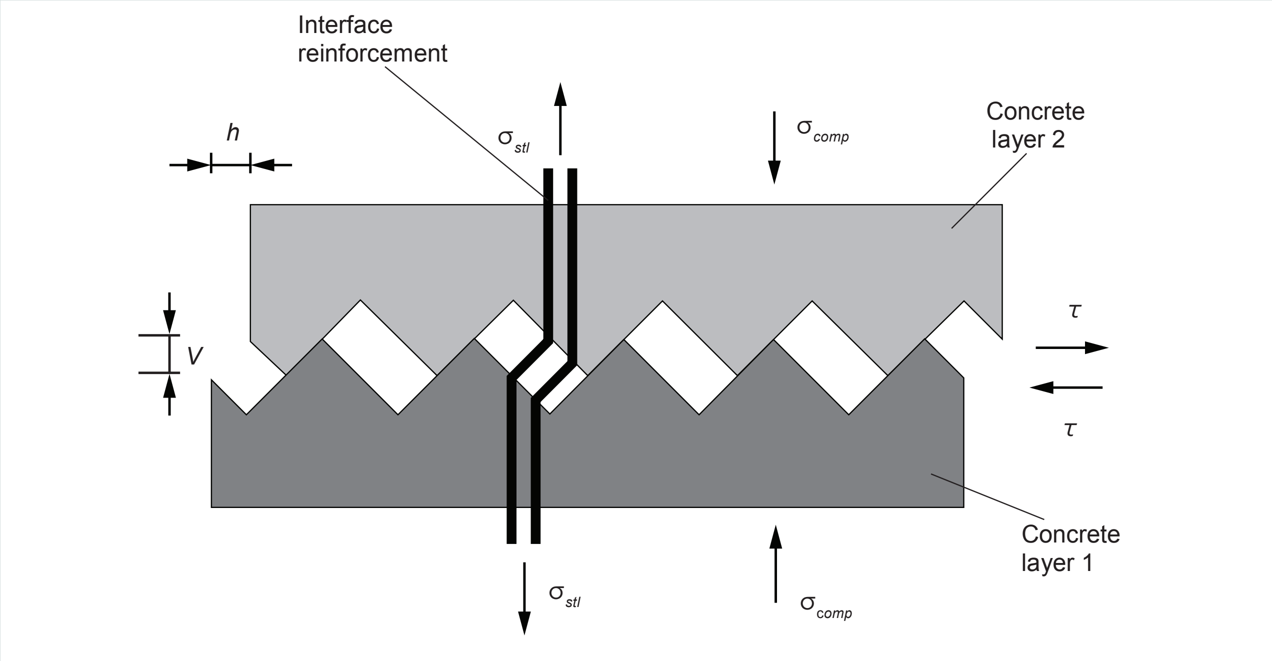


Figure 2. Interface shear transfer, sawtooth model.
Source: Data from Santos and Júlio (2012).
Note: h = horizontal displacement; v = vertical displacement; σ_{comp} = compressive stress perpendicular to the interface; σ_{stl} = tensile stress developed in steel reinforcement due to shear-friction; τ = shear stress developed at the interface.

Table 1. Factors for use in metric (MPa) interface-shear-transfer model based on AASHTO LRFD specifications

Condition	c	μ	K_1	K_2
Cast-in-place concrete slab on clean concrete girder surfaces, free of laitance, surface roughened to an amplitude of 6 mm	1.93	1	0.3	12.41 (normalweight concrete) 8.96 (lightweight concrete)
Normalweight concrete placed monolithically	2.76	1.4	0.25	10.34
Lightweight concrete placed monolithically or nonmonolithically against a clean concrete surface, free of laitance, surface roughened to an amplitude of 6 mm	1.65	1	0.25	6.89
Normalweight concrete placed against a clean concrete surface, free of laitance, with surface intentionally roughened to an amplitude of 6 mm	1.65	1	0.25	10.34
Concrete placed against a clean concrete surface, free of laitance, but not intentionally roughened	0.52	0.6	0.2	5.52
Concrete anchored to as-rolled structural steel by headed studs or by reinforcing bars where all steel in contact with concrete is clean and free of paint	0.17	0.7	0.2	5.52

Note: c = cohesion factor; K_1 = fraction of concrete strength available to resist interface shear; K_2 = limiting interface shear resistance; μ = friction factor. 1 mm = 0.0394 in.

These coefficients are calculated in Eq. (7) to (9).

$$C = k_1 \frac{R}{6} + k_2 f_c' \tag{7}$$

$$M_1 = k_3 \frac{R}{6} + k_4 \frac{f_c}{34} \tag{8}$$

$$M_2 = k_5 \frac{R}{6} + k_6 \frac{f_c'}{34} \tag{9}$$

where

k_1 = cohesion factor applied to R = 0.035 MPa

k_2 = cohesion factor applied to f_c' = 0.001 MPa

k_3 = shear friction factor applied to R = 0 MPa

k_4 = shear friction factor applied to f_c' = 0.015 MPa

k_5 = normal force friction factor applied to R = 0.8 MPa for normalweight concrete and 1.7 MPa for lightweight concrete

k_6 = normal force friction factor applied to f_c' = 15.0 MPa for normalweight concrete and 0 MPa for lightweight concrete

The units of V_{pre}, A_{cv}, A_{vf}, f_y, P_c, R, and f_c' are kN, mm^2, mm^2, MPa, kN, mm, and MPa, respectively. The k_1 to k_6 factors were determined through the application of a multiple linear regression analysis conducted in the previous study.[3]

Previous reliability studies of the AASHTO LRFD specifications IST model

Scott[9] performed 36 push-off tests (the most conventional IST test method) to determine whether the current code equations accurately predict the horizontal shear strength at the connection of precast concrete girders and cast-in-place concrete decks for both normalweight and lightweight concrete members.[3] A structural reliability analysis showed that the 2007 AASHTO LRFD specifications[10] resistance factors provided a reliability index of 2.88 and 3.27 for normalweight concrete and lightweight concrete, respectively. The present study considered the minimum reinforcement requirement of the 2014 AASHTO LRFD specifications, unlike Scott's work, which considered the 2007 edition.

Lang[11] created a database with data from 537 tests from previous research. A reliability analysis performed on the database showed that the reliability indices for normalweight concrete were 0.95 and 1.20 for rough and smooth interface roughness conditions, respectively. For lightweight concrete, the indices were 2.40 and 1.50 for rough and smooth interface roughness conditions, respectively. The present study differs from Lang's research in that it includes updated test data, focuses exclusively on uncracked reinforced specimens, and considers the minimum reinforcement requirements of the 2014 AASHTO LRFD specifications.

Reliability analysis

The most important objective in engineering design is to ensure structural safety, which relates to applied loads and structural resistance. Some of the uncertainties that result from the inherent variability in load and resistance models can be quantified through the application of reliability theory and eventually be taken into account in design codes. Reliability is a measure of the probability of a structural failure, which is defined within the context of a limit state (the boundary between desired and undesired performance). The load model Q and the resistance model R_m are considered to be random variables in the structural reliability analysis. Per Nowak and Collins[12] and Robert,[13] the structural reliability or survival probability of structures p_s is given by Eq. (10).

$$p_s = P(R_m - Q > 0) \tag{10}$$

This is the survival probability of the structural system if the resistance value is more than the load value. Considering Eq. (10), the failure probability p_f is determined by Eq. (11).

$$p_f = P(R_m - Q < 0) \tag{11}$$

The reliability index β, which is related to the failure probability p_f, is defined by Eq. (12).

$$\beta = -\phi^{-1}(p_f) \tag{12}$$

where

$\phi^{-1}()$ = inverse standard normal distribution function

If R_m and Q are normally distributed, random, and independent variables, the reliability index can be determined by Eq. (13).

$$\beta = \frac{m_{R_m} - m_Q}{\sigma_{R_m}^2 + \sigma_Q^2} \tag{13}$$

where

m_{R_m} = mean value of resistance model

m_Q = mean value of load model

σ_{R_m} = standard deviation of resistance model

σ_Q = standard deviation of load model

Statistical details of the resistance model

The AASHTO LRFD specifications consider the limit state factored load combination for horizontal shear resistance at the interface of a bridge deck and bridge girder to be a Strength I load combination. Thus, Eq. (1) in the 2014 AASHTO LRFD specifications is defined as Eq. (14).

$$\gamma_{DC}DC + \gamma_{DW}DW + \gamma_{LL}(LL + IM) = \phi V_{ni} \tag{14}$$

where

γ_{DC} = load factor of $DC = 1.25$ in the AASHTO LRFD specifications Strength I load combination

DC = dead load from the weight of structural components and nonstructural attachments

γ_{DW} = load factor of $DW = 1.50$ in the AASHTO LRFD specifications Strength I load combination

DW = dead load from the weight of the wearing surface

γ_{LL} = load factor of $LL = 1.75$ in the AASHTO LRFD specifications Strength I load combination

LL = live load from the forces from moving vehicles on the bridge

IM = impact load from the forces produced by moving vehicles on the bridge

From Eq. (14), the nominal resistance V_{ni} can be written as Eq. (15).

$$V_{ni} = \frac{\gamma_{DC}DC + \gamma_{DW}DW + \gamma_{LL}(LL + IM)}{\phi} \tag{15}$$

The resistance model can be written as Eq. (16).

$$R = V_{ni}MFP \tag{16}$$

where

M = material factor

F = fabrication factor

P = professional factor

The material factor accounts for variation in material properties affecting the IST, including compressive strength of concrete, yield strength of reinforcement, and so forth. The fabrication factor reflects variation in member geometry, such as dimensions, moment of inertia, and reinforcement placement. The professional factor represents the accuracy of the IST model. The mean m_{R_m} and coefficient of variation COV_{R_m} values of the resistance model are given by Eq. (17) and (18), respectively.

$$m_{R_m} = V_{ni}\lambda_M\lambda_F\lambda_P \tag{17}$$

where

λ_M = mean value of M

λ_F = mean value of F

λ_P = mean value of P

$$COV_{R_m} = \sqrt{COV_M^2 + COV_F^2 + COV_P^2} \tag{18}$$

where

Table 2. Statistical parameters of resistance model

Statistical parameters		Bias factor λ	Coefficient of variation
Material factor *M*		1.22	0.12
Fabrication factor *F*		1.01	0.04
Professional factor *P* (Soltani et al. 2018)	Normalweight concrete	1.28	0.27
	Lightweight concrete	1.30	0.19
Professional factor *P* (AASHTO LRFD specifications)	Normalweight concrete	1.62	0.45
	Lightweight concrete	1.42	0.24

COV_M = coefficient of variation of M

COV_F = coefficient of variation of F

COV_P = coefficient of variation of P

For the professional factor, Eq. (3) (AASHTO LRFD specifications) and Eq. (6) (Soltani et al.) were used to predict the IST nominal resistance in two categories: normalweight concrete and lightweight concrete. **Table 2** summarizes the statistical parameters of resistance used in this study, based on previous research.[14]

Statistical details of the load model

The load model Q is given by Eq. (19).

$$Q = DC + DW + (LL + IM) \tag{19}$$

The mean m_Q and coefficient of variation COV_Q values of the load model are given by Eq. (20) and (21), respectively.

$$m_Q = DC\lambda_{DC} + DW\lambda_{DW} + (LL + IM)\lambda_{LL+IM} \tag{20}$$

where

λ_{DC} = bias factor of DC

λ_{DW} = bias factor of DW

λ_{LL+IM} = bias factor of $LL + IM$

$$COV_Q = \sqrt{COV_{DC}^2 + COV_{DW}^2 + COV_{LL+IM}^2} \tag{21}$$

where

COV_{DC} = coefficient of variation of DC

COV_{DW} = coefficient of variation of DW

COV_{LL+IM} = coefficient of variation of $LL + IM$

Table 3 gives the bias factors and coefficients of variation of the load model.[15]

Results and discussion

Normality of the IST professional factors

The professional factor, bias factor, and coefficient of variation were calculated from the ratio of experimental IST strength to nominal IST strength predicted by the AASHTO LRFD specifications (Eq. [3]) and Soltani et al.'s IST model (Eq. [6]) using the IST database created by Soltani and Ross.[1] The statistical parameters were computed for normalweight and lightweight concrete (Table 2). To use Eq. (13), the normality of the resistance and load models needs to be checked. The load model has a normal distribution because all of the parameters used in the equation have normal distributions. However, in the resistance model, the professional factor needs to be checked. To check the normality of distributions of P, the standard normal variable Z_{value} was calculated using Eq. (22).

$$Z_{value} = \frac{\left({}^{V_{exp}}\!/_{V_n}\right)_i - Avg\left({}^{V_{exp}}\!/_{V_n}\right)}{SD\,{}^{V_{exp}}\!/_{V_n}} \tag{22}$$

where

V_{exp} = measured experimental IST strength (for the sample number of i)

V_n = predicted nominal IST strength (for the sample number of i)

Table 3. Statistical parameters of load model

Statistical parameters	Bias factor λ	Coefficient of variation
DC	1.05	0.10
DW	1.05	0.25
LL + *IM*	1.28	0.18

Note: *DC* = dead load from the weight of structural components and nonstructural attachments; *DW* = dead load from the weight of the wearing surface; *IM* = impact load from the forces produced by moving vehicles on the bridge; *LL* = live load from the forces produced by moving vehicles on the bridge.

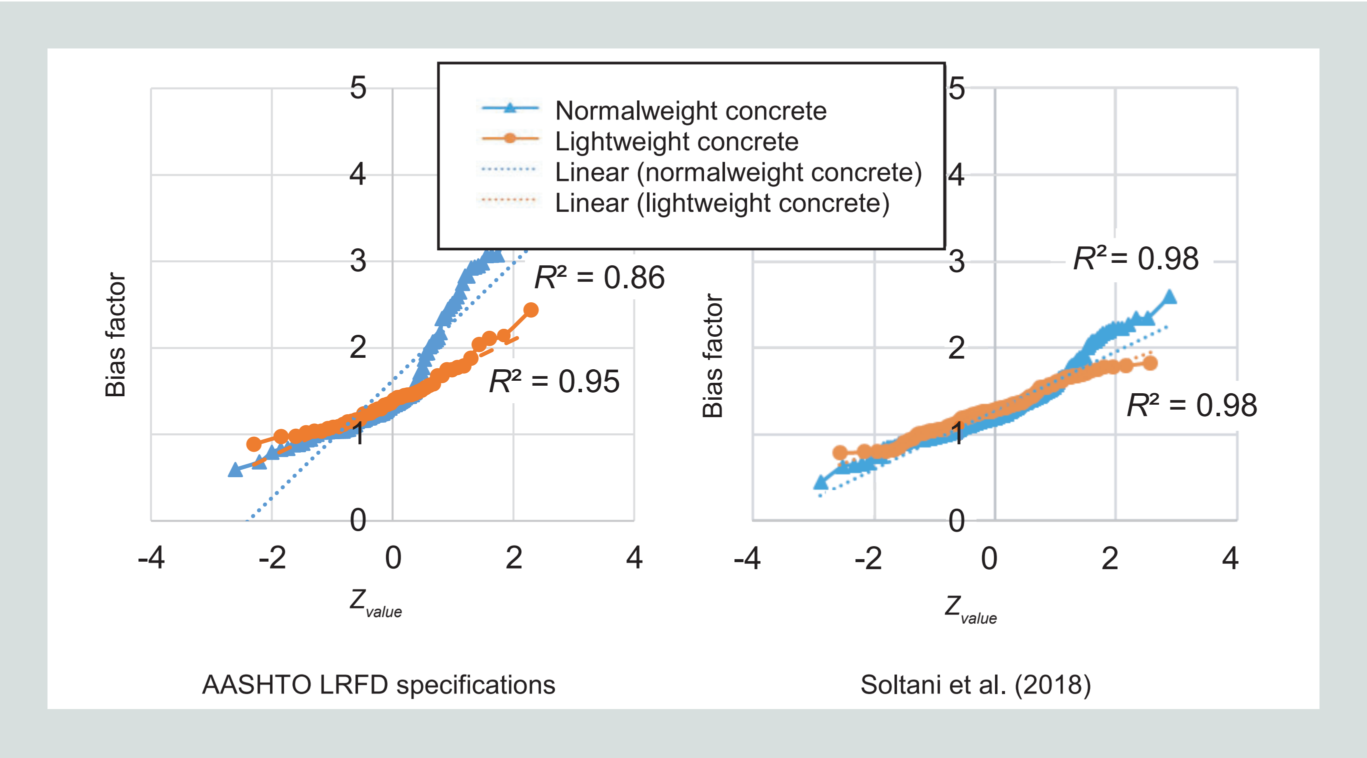


Figure 3. Normal variable distributions of interface-shear-transfer models. Note: R = roughness amplitude of interface; Z_{value} = standard normal variable.

$Avg\left(V_{exp}/V_n\right)$ = mean value of the strength ratios

$SD\left(V_{exp}/V_n\right)$ = standard deviation of the strength ratios

If the professional factor is normally distributed, the data in the graph will be in an approximately straight line. **Figure 3** illustrates the test data in both categories, normalweight concrete and lightweight concrete, for each IST model. Considering the linear regression of the bias factors and Z_{value}, the minimum value of the statistical parameter R^2 is 0.86, and the maximum professional factor P value is 5.96×10^{-48}. These values indicate that the professional factor P is normally distributed in both categories.

Reliability analysis

The data in each model were separated into two categories: normalweight concrete and lightweight concrete. In the AASHTO LRFD specifications database, there were 109 tests with normalweight concrete and 46 tests with lightweight concrete.

In Soltani et al.'s model database, there were 256 tests with normalweight concrete and 98 tests with lightweight concrete. To investigate the reliability indices for different load values, the reliability indices were calculated using Eq. (23) and (24) for a dead load ratio DR and live load ratio LR, respectively.

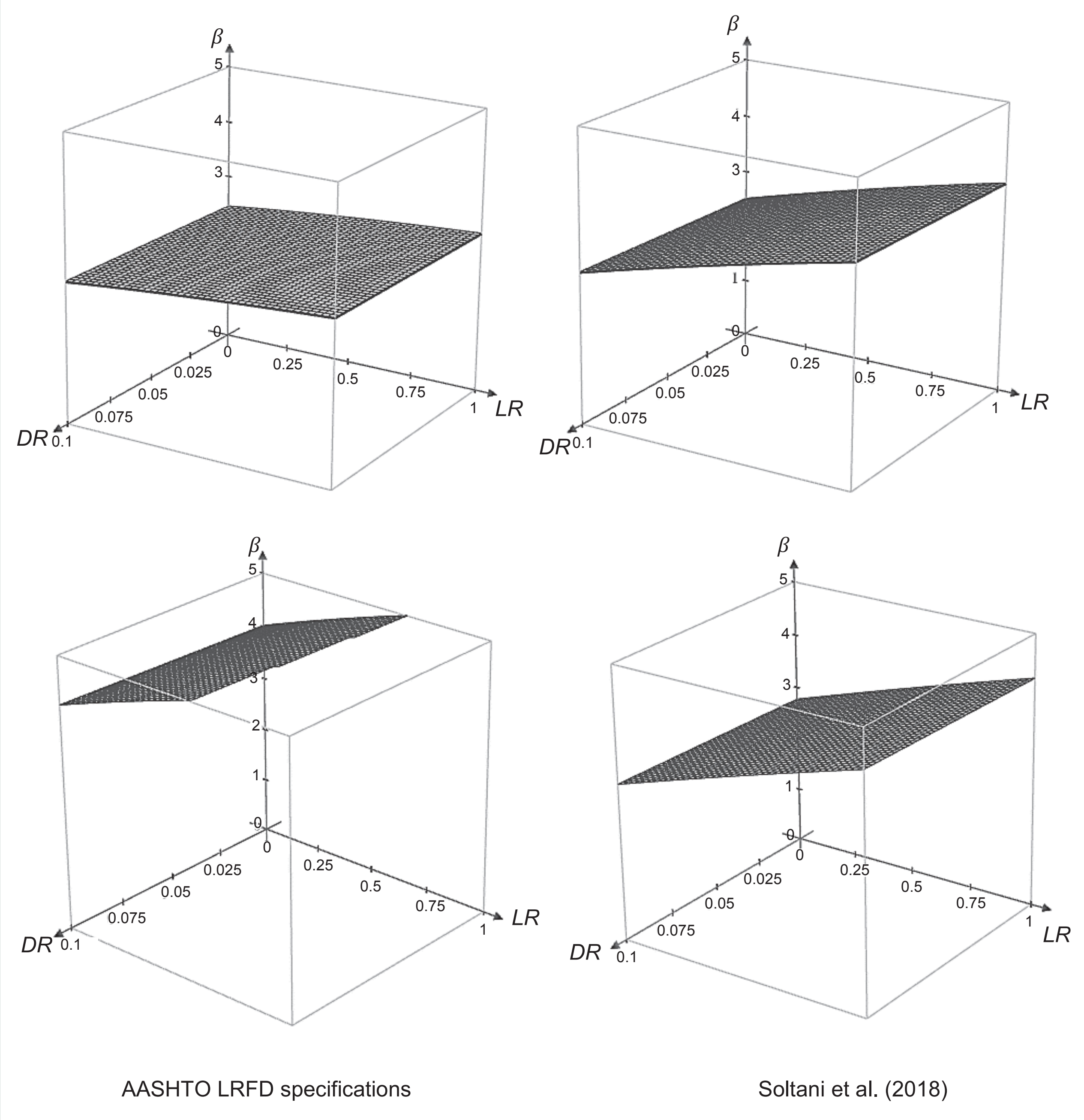
$$DR = \frac{DW}{DC + DW + (LL + IM)} \tag{23}$$

$$LR = \frac{(LL + IM)}{DC + DW + (LL + IM)} \tag{24}$$

The resistance factor ϕ, used in Eq. (15) to calculate the reliability index from Soltani et al.'s model, was adjusted to 0.95. With this value, Soltani et al.'s model calculated the reliability index to be approximately 3.50, which is the target reliability index of most structural design codes, such as the AASHTO LRFD specifications. This target value of 3.50 means that the probability of failure is approximately equal to 0.04%.

Figure 4 compares the reliability index with the dead load ratios DR from the wearing surface and the live load ratios LR. In the AASHTO LRFD specifications model, the reliability indices of normalweight concrete are generally less than the target reliability index of 3.50, while the reliability indices of lightweight concrete are generally greater. The reliability index plane of normalweight concrete is generally less than 3.0 (Fig. 4), whereas the reliability index plane of lightweight concrete is generally greater than 4.0. In Soltani et al.'s model, the reliability indices of normalweight and lightweight concrete are both around 3.50. The shapes and values of the reliability index planes are also similar in both categories.

To compare the reliability index as just one number for each model, an example of a critical loading scenario (DR and LR values) was chosen from the 2014 *PCI Bridge Design Manual*.[16] According to Tables 9.1a.4-1 and 2, the maximum shear values of the wearing surface V_{ws}, barrier weight V_b, and lane load plus truck load with impact $V_{LL} + V_{LT}$ were



AASHTO LRFD specifications

Soltani et al. (2018)

Figure 4. Percentage of live load and dead load from wearing surface versus reliability index for normalweight concrete (top) and lightweight concrete (bottom). Note: *DR* = dead load ratio; *LR* = live load ratio; *β* = reliability index.

equal to 53, 27, and 498 kN (12, 6, and 112 kip), respectively. Thus, DR and LR were calculated to be 0.10 and 0.86 using Eq. (23) and (24), respectively. As previously mentioned, the resistance factor ϕ of the AASHTO LRFD specifications IST model is 0.9 for normalweight concrete and 0.8 for lightweight concrete.

To investigate influence of the resistance factor, reliability indices were determined for a range of resistance factors (**Fig. 5**). Following this scenario, the target reliability index of 3.50 was satisfied with the resistance factors. In Soltani et al.'s[3] model with normalweight concrete, the resistance factor should be 0.95 to reach to the target reliability index of 3.5; this model with lightweight concrete needs to have the resistance factor of 1.00, which leads to the reliability index of 3.78. In AASHTO LRFD specifications with normalweight concrete, the resistance factor has to be equal to 0.55 to reach to the target reliability index and 1.00 for tests with lightweight concrete (it produces reliability index of 4.05).

The AASHTO LRFD specifications IST model was conservative for lightweight concrete (no need for any resistance factor

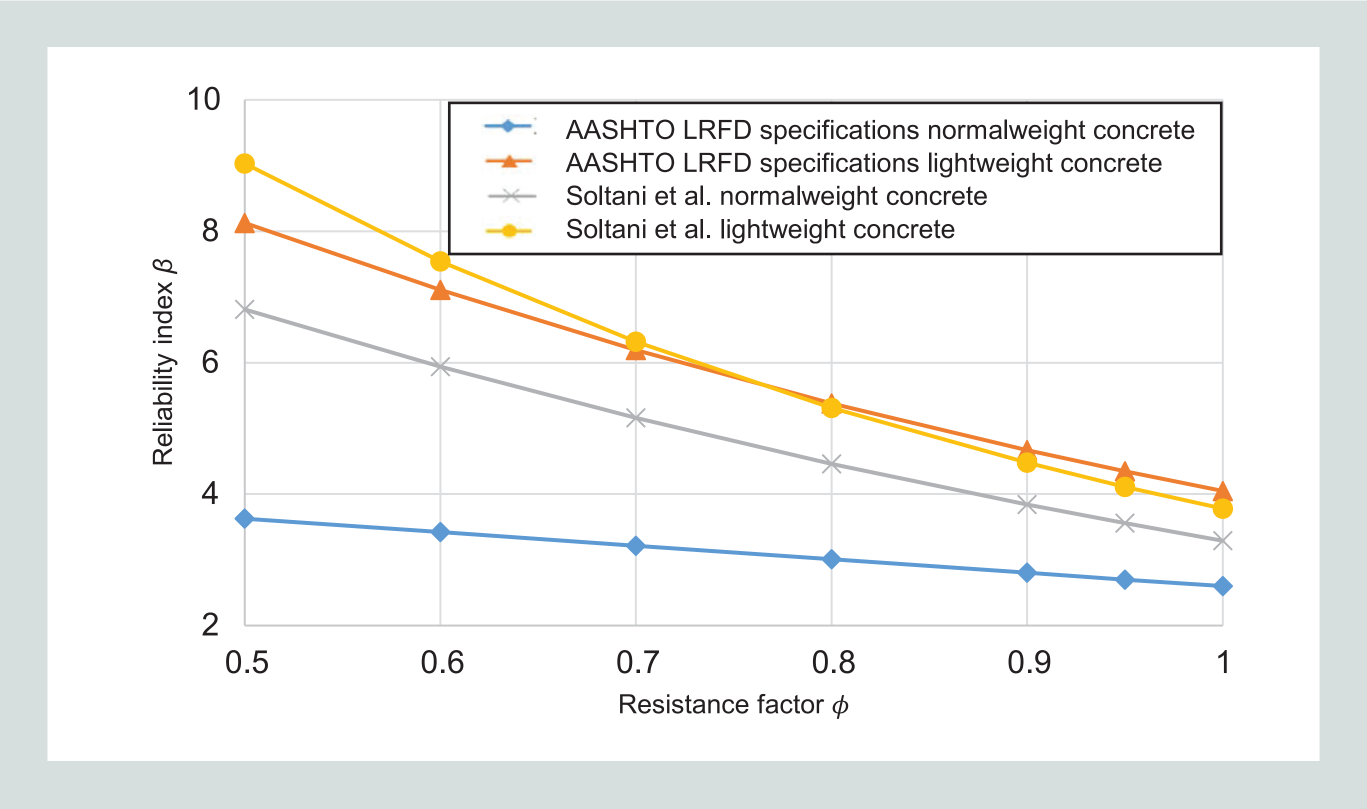


Figure 5. Reliability indices for different resistance factors.

[ϕ equal to 1]); however, it was significantly unconservative for normalweight concrete. In the latter case, a resistance factor of 0.55 was needed to satisfy the target reliability index of 3.50. The AASHTO LRFD specifications–based resistance factors led to reliability indices of 2.80 (p_f equal to 0.3%) and 5.38 (p_f equal to 6×10^{-5}%) for normalweight concrete and lightweight concrete, respectively. Hence, the target reliability index was not satisfied for either normalweight concrete or lightweight concrete tests. Alternatively, the resistance factors used in Soltani et al.'s model successfully met the target reliability index of 3.50. The resistance factor of 0.95 in Soltani et al.'s model led to reliability indices of 3.56 (p_f equal to 0.04%) and 4.11 (p_f equal to 0.01%) for normalweight concrete and lightweight concrete, respectively.

Parametric reliability analysis

A bin analysis was also performed to evaluate the relationships between the reliability index and IST design variables, including the area of concrete interface A_{cv}, interface shear reinforcement index ρf_y, compressive strength of concrete f'_c, roughness amplitude of interface R, and compressive force normal to the shear plane P_c. These design variables were selected for investigation because they affect IST capacity and are used in both the AASHTO LRFD specifications model and Soltani et al.'s model.[3] The interface reinforcement index ρf_y is calculated using Eq. (25).

$$\rho f_y = \frac{A_{vf}}{A_{cv}} f_y \qquad (25)$$

The range of the roughness amplitude of interface R and compressive force normal to the shear plane P_c were each divided into two categories. The roughness amplitude of interface categories was greater than 0.3 mm (0.1 in.) and less than 0.3 mm. The compressive force normal to the shear plane was divided into tests with zero compressive force and tests with nonzero compressive force. These categorizations were selected based on the characteristics of tests in the database.[1]

For the rest of the design variables, the range of each variable was divided into four and three equally spaced bins for normalweight concrete and lightweight concrete, respectively. Both models had more normalweight concrete tests than lightweight concrete; thus, to have a comparable number of tests, more normalweight concrete bins were defined than lightweight concrete bins.

Tables 4 and **5** show the bias factor, coefficient of variation, and number of tests for each bin. The bias factors for tests with normalweight concrete ranged from 1.20 to 2.64 in the AASHTO LRFD specifications model and from 1.13 to 1.50 in Soltani et al.'s model. Tests with lightweight concrete had bias factors ranging from 1.30 to 1.53 in the AASHTO LRFD specifications model and from 1.12 to 1.41 in Soltani et al.'s model. Thus, Soltani et al.'s model was generally more accurate than the AASHTO LRFD specifications model. The coefficients of variation ranged from 0.11 to 0.49 and from 0.14 to 0.30 in the AASHTO LRFD specifications model and Soltani et al.'s model, respectively.

Table 4. Statistical information of evaluating bins for normalweight concrete

Source	Parameter	f'_c, MPa				ρf_y, MPa				A_{cv}, mm^2				R, mm		P_c, kN	
		<28	28-41	41-55	>55	<0.3	0.3-2.8	2.8-5.5	>5.5	<64,500	64,500-96,800	96,800-129,000	>129,000	<3	>3	0	≠0
AASHTO LRFD specifications	λ	1.41	1.24	1.46	2.64	n.d.	1.65	1.71	1.51	1.87	1.54	1.20	1.20	2.57	1.32	1.67	1.29
	COV	0.30	0.33	0.44	0.23		0.43	0.49	0.43	0.44	0.42	0.11	0.27	0.70	0.41	0.45	0.42
	Number of tests	18	51	15	25		32	36	41	57	22	16	14	26	83	96	13
Soltani et al. (2018)	λ	1.42	1.24	1.28	1.21	1.15	1.33	1.46	1.50	1.50	1.25	1.15	1.13	1.31	1.26	1.31	1.18
	COV	0.30	0.30	0.20	0.15	0.19	0.32	0.30	0.25	0.27	0.20	0.22	0.27	0.28	0.27	0.30	0.12
	Number of tests	70	111	18	57	139	35	39	43	87	46	94	29	110	144	204	52

Note: A_{cv} = area of concrete considered to be engaged in interface shear transfer; *COV* = coefficient of variation; f'_c = compressive strength of concrete; n.d. = no data in the bin; P_c = permanent net compressive force normal to the shear plane; R = roughness amplitude of interface; λ = bias factor; ρf_y = interface reinforcement index. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

Table 5. Statistical information of evaluating bins for lightweight concrete

Source	Parameter	f'_c, MPa			ρf_y, MPa			A_{cv}, mm^2			R, mm		P_c, kN	
		<28	28–41	>41	< 0.3	0.3–2.8	>2.8	<64,500	64,500–129,000	>129,000	<3	>3	0	≠0
AASHTO LRFD specifications	λ	n.d.	1.30	1.53	n.d.	1.41	1.43	1.47	1.47	1.31	1.61	1.25	1.45	1.39
	COV		0.21	0.24		0.27	0.22	0.26	0.18	0.23	0.33	0.26	0.27	0.21
	Number of tests		22	24		22	24	26	6	14	22	24	24	22
Soltani et al. (2018)	λ	1.32	1.25	1.33	1.25	1.25	1.41	1.35	1.12	1.28	1.30	1.27	1.41	1.27
	COV	0.21	0.23	0.14	0.24	0.19	0.14	0.18	0.20	0.19	0.28	0.27	0.13	0.21
	Number of tests	36	32	30	27	40	31	60	16	22	24	74	24	74

Note: A_{cv} = area of concrete considered to be engaged in interface shear transfer; *COV* = coefficient of variation; f'_c = compressive strength of concrete; n.d. = no data in the bin; P_c = permanent net compressive force normal to the shear plane; R = roughness amplitude of interface; λ = bias factor; ρf_y = interface reinforcement index. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

This shows that Soltani et al.'s model is consistently more accurate throughout the ranges of design variables than the AASHTO LRFD specifications model. In some bins of the AASHTO LRFD specifications model, there were no data to compare with similar bins of Soltani et al.'s model. This was due to requirements in the AASHTO LRFD specifications, such as minimum compressive strength of concrete and minimum interface reinforcement of tests. These limitations do not exist in Soltani et al.'s model. **Figure 6** illustrates the reliability indices related to each bin of IST design variables, including compressive strength of concrete, interface reinforcement index, area of concrete interface, roughness amplitude of interface, and compressive force normal to the shear plane. The results of this analysis will help designers and practitioners produce reliable designs. The investigation of the reliability index with respect to each design variable is discussed in the following sections.

Compressive strength of concrete f'_c

For normalweight concrete with f'_c between 41 and 55 MPa (5.9 and 8.0 ksi), the AASHTO LRFD specifications reliability index was 2.75 (below the target reliability index), which is significantly higher than the target reliability index when f'_c is greater than 55 MPa. The reliability indices of Soltani et al.'s model were more consistent than those of the AASHTO LRFD specifications IST model, and averaged around 3.50 for all bins.

For lightweight concrete, the reliability indices of Soltani et al.'s model for all bins ranged from 3.34 to 3.91. When the compressive strength of concrete was greater than 28 MPa (4.1 ksi), the AASHTO LRFD specifications reliability indices were higher than the target reliability index of 3.5.

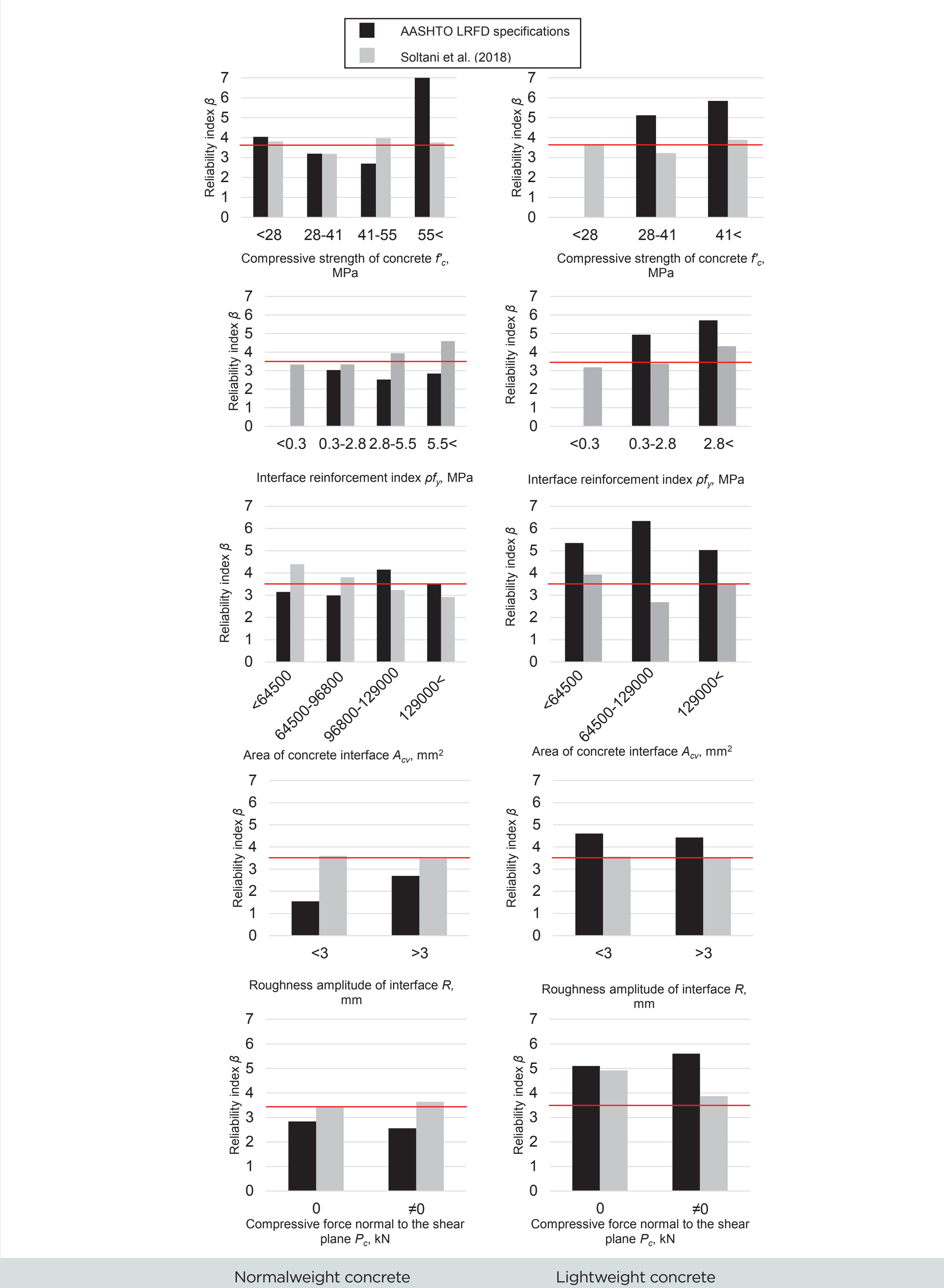


Figure 6. Reliability indices for ranges of design variables. Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

Interface reinforcement index ρf_y

In the tests with normalweight concrete using Soltani et al.'s model, more interface reinforcement led to higher values of reliability index. The lowest reliability index was 2.62 in the AASHTO LRFD specifications model, when the interface reinforcement index was between 2.8 and 5.5 MPa (0.41 and 0.80 ksi). The reliability indices for the tests with lightweight concrete in all bins of the AASHTO LRFD specifications model were too high compared with the target reliability index. However, the reliability indices were consistent, with an average of approximately 3.50 for Soltani et al.'s model.

Area of concrete interface A_{cv}

For normalweight concrete, when the area of concrete interface was between 64,500 and 96,800 mm^2 (100 and 150 in.^{2}), the AASHTO LRFD specifications reliability index was the lowest (β equal to 2.98). In Soltani et al.'s model, the highest reliability index was obtained when the area of concrete interface was less than 64,500 mm^2 (100 in.^{2}). For the tests with lightweight concrete, the minimum AASHTO LRFD specifications reliability index was 4.99. However, the minimum reliability index of Soltani et al.'s model was 2.69 when the area of concrete interface was between 64,500 and 129,000 mm^2 (100 and 200 in.^{2}).

Roughness amplitude of interface R

For the tests with normalweight concrete, the AASHTO LRFD specifications reliability index was 2.70 for a roughness amplitude of interface greater than 3 mm (0.1 in.) and 1.55 for a roughness amplitude of interface less than 3 mm. Thus, the AASHTO LRFD specifications model was 1.74 times more reliable when the interface was roughened compared with smooth interfaces. However, Soltani et al.'s model showed consistent reliability index values for both interface roughness scenarios (β of about 3.5). The minimum reliability index for the tests with lightweight concrete using the AASHTO LRFD specifications model was 4.5, which is higher than the target reliability index.

Compressive force normal to the shear plane P_c

The AASHTO LRFD specifications reliability indices do not relate to the compressive force normal to the shear plane. The reliability index for tests with normalweight concrete was less than 2.87, with or without the presence of a normal force. However, for tests with normalweight concrete using Soltani et al.'s model, the reliability index was around 3.50 in both P_c scenarios. Considering lightweight concrete with no normal force applied, the reliability index of Soltani et al.'s model was 4.95. The AASHTO LRFD specifications reliability index was higher than the target reliability index in both P_c scenarios.

The results of the parametric study show that the AASHTO LRFD specifications reliability index values depend on the values of the design variables. However, the reliability indices of Soltani et al.'s model were more consistent for different ranges of the design variables compared with the AASHTO LRFD specifications model and also averaged around the target reliability index of 3.50.

Conclusion

Reliability analyses were performed on the IST model of the 2014 AASHTO LRFD specifications and on Soltani et al.'s revised IST model to evaluate and determine their respective resistance factors. The analyses considered members with normalweight and lightweight concrete. Source data for the analyses were from a database presented in Soltani and Ross.[1] To perform the reliability analyses, a resistance model R and a load model Q were created for each IST model. The reliability indices were obtained under a critical load scenario in which the shear values of the wearing surface, barrier weight, and lane load plus truck load with impact were determined to be 53, 27, and 498 kN (12, 6.1, and 112 kip), respectively. The reliability index of the current AASHTO LRFD specifications IST model was reported. Considering the target reliability index of 3.50, a resistance factor was proposed for Soltani et al.'s model. Finally, reliability analyses using bin analysis were performed on ranges of design variables, including the compressive strength of concrete f_c', area of concrete interface A_{cv}, interface reinforcement index ρf_y, roughness amplitude of interface R, and compressive force normal to the shear plane P_c.

The resistance factors of 0.9 (normalweight concrete) and 0.8 (lightweight concrete) in the AASHTO LRFD specifications model led to reliability indices of 2.80 and 5.38 for normalweight and lightweight concrete, respectively. For the tests with normalweight concrete, a resistance factor of 0.55 resulted in the target reliability index of 3.50. The reliability index of the current AASHTO LRFD specifications IST model for normalweight concrete tests is lower than the target reliability index, while the AASHTO LRFD specifications IST model for lightweight concrete is too conservative (no resistance factor needed to satisfy the target reliability index). These results showed the need to revise the AASHTO LRFD specifications IST model and the resistance factors associated with it.

The resistance factor of 0.95 for both normalweight and lightweight concrete in Soltani et al.'s model resulted in reliability indices of 3.56 and 4.11 for normalweight and lightweight concrete, respectively. This shows that Soltani et al.'s model met the target reliability index requirement through applying only one resistance factor for both normalweight and lightweight concrete. Therefore, Soltani et al.'s model is an appropriate alternative to the current AASHTO LRFD specifications IST model.

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Notation

A_{cv} = area of concrete engaged in interface shear transfer

A_{vf} = area of interface shear reinforcement crossing the shear plane within the area A_{cv}

$Avg\left(V_{exp}/V_n\right)$ = mean value of the strength ratios

c = cohesion factor

C = cohesion coefficient

COV_{DC} = coefficient of variation of DC

COV_{DW} = coefficient of variation of DW

COV_F = coefficient of variation of F

COV_{LL+IM} = coefficient of variation of $LL + IM$

COV_M = coefficient of variation of M

COV_P = coefficient of variation of P

COV_Q = coefficient of variation of the load model

COV_R = coefficient of variation of the resistance model

DC = dead load from the weight of structural components and nonstructural attachments

DR = dead load ratio

DW = dead load from the weight of the wearing surface

f_c' = compressive strength of concrete

f_y = yield stress of reinforcement

F = fabrication factor

h = horizontal displacement

IM = impact load from the forces produced by moving vehicles on the bridge

k_1 = cohesion factor applied to R

k_2 = cohesion factor applied to f_c'

k_3 = shear friction factor applied to R

k_4 = shear friction factor applied to f_c'

k_5 = normal force friction factor applied to R

k_6 = normal force friction factor applied to f_c'

K_1 = fraction of concrete strength available to resist interface shear

K_2 = limiting interface shear resistance

LL = live load from the forces from moving vehicles on the bridge

LR = live load ratio

m_Q = mean value of the load model

m_{RM} = mean value of the resistance model

M = material factor

M_1 = friction coefficient for the shear-friction mechanism

M_2 = friction coefficient for the normal force

p_f = failure probability

p_s = survival probability

P = professional factor

P_c = compressive force normal to the shear plane

Q = load model

R = roughness amplitude of interface

R_m = resistance model

$SD\left(V_{exp}/V_n\right)$ = standard deviation of the strength ratios

v = vertical displacement

V_b = barrier weight maximum shear

V_{exp} = measured experimental interface shear transfer strength

V_{LL} = lane load maximum shear

V_{LT} = truck load maximum shear

V_n = predicted nominal interface shear transfer strength

V_{ni} = nominal interface shear resistance according to the AASHTO LRFD specifications

V_{pre} = predicted interface shear transfer strength

V_{ri} = factored interface shear resistance

V_{ui} = factored interface shear force due to the total load based on the applicable strength and extreme-event load combinations

V_{ws} = wearing surface maximum shear

Z_{value} = standard normal variable

β = reliability index

γ_{DC} = load factor of DC

γ_{DW} = load factor of DW

γ_{LL} = load factor of LL

λ = bias factor

λ_{DC} = bias factor of DC

λ_{DW} = bias factor of DW

λ_F = mean value of F

λ_{LL+IM} = bias factor of $LL + IM$

λ_M = mean value of M

λ_P = mean value of P

μ = friction factor

ρf_y = interface reinforcement index

σ_{comp} = compressive stress perpendicular to the interface

σ_Q = standard deviation of load model

σ_R = standard deviation of resistance model

σ_{stl} = tensile stress developed in steel reinforcement due to shear-friction

τ = shear stress developed at the interface

ϕ = shear resistance factor

$\phi^{-1}()$ = inverse standard normal distribution function

About the author

Mahmoodreza Soltani, PhD, is a postdoctoral researcher/lecturer in the Glenn Department of Civil Engineering at Clemson University in Clemson, S.C. He received his bachelor's degree from Shahid Beheshti University in Tehran, Iran; his master's degree from the University of Texas at El Paso, Tex.; and his PhD from Clemson University. His research interests include the behavior, analysis, and design of reinforced and prestressed concrete structures and bridge engineering and reliability analysis of civil engineering systems.

Abstract

Interface shear transfer (IST) is a concept that describes the mechanisms by which shear forces pass through a concrete-to-concrete interface where no, or negligible, moment is present. Previous research has shown that the IST model of the 2014 American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* produces inconsistent levels of accuracy for different values of design variables, such as compressive strength of concrete. In this study, a reliability analysis was performed on the AASHTO LRFD specifications model to evaluate the code's resistance factor. In addition, a comparative reliability analysis was performed on a new IST model that improves the limitations of the AASHTO LRFD specifications model to calibrate its resistance factor to meet the target reliability index of 3.50. Results showed that for a critical load combination, the reliability indices of the AASHTO LRFD specifications model with normalweight and lightweight concrete were 2.80 and 5.38, respectively, whereas applying a resistance factor of 0.95, the reliability indices of the alternative IST model for tests with normalweight concrete and lightweight concrete were 3.56 and 4.11, respectively. The results of the reliability study show that the alternative model performs better than the AASHTO LRFD specifications model. In this study, reliability indices were also scrutinized for different ranges of IST design variables, which benefits designers and practitioners.

Keywords

Design model, interface shear transfer design variables, lightweight concrete, load model, normalweight concrete, resistance factor, resistance model, shear friction.

Review policy

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

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