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Research Article

Mechanical Model for Shear Friction Capacity of Concrete at Construction Joints

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This study examined the reliability and limitations of code equations for determining the shear friction strength of a concrete interface with construction joints. This was achieved by examining the code equations (ACI 318-14, AASHTO, and *fib* 2010) and comparing the results predicted by equations with experimental data compiled from 207 push-off specimens (133 rough and 74 smooth construction joints). The integrated mechanical model for the monolithic interface, derived from the upper-bound theorem of concrete plasticity, was also modified to estimate the shear friction strength of the construction joints. The upper limit for shear friction strength was formulated from a concrete crushing failure limit on the strut-and-tie action along the interfacial plane, to avoid overestimating the shear transfer capacity of transverse reinforcement with a high clamping force. Code equations are highly conservative and dispersive in predicting the shear friction strength of rough construction joints and yield large scattering in the data for the ratios between the measured and predicted shear friction strengths. The predictions obtained using the proposed model agreed well with test results, indicating correlating trends with the test results for evaluating the effects of various parameters on the shear friction strength of rough construction joints. According to the proposed model, the values of cohesion and coefficient of friction for concrete could be determined as 0.11 $(f_c')^{0.65}$ and 0.64, respectively, for smooth construction joints and 0.27 $(f_c')^{0.65}$ and 0.95, respectively, for rough construction joints, where f_c' is the compressive strength of concrete.

1. Introduction

Shear friction is generally accepted as a major mechanism of load transfer along a concrete-to-concrete interface, which is subjected to simultaneous shear and normal stresses. The crack propagation and failure plane of a member governed by shear friction are concentrated on the interfacial shear plane [1–3]. Despite the fact that the mechanism of shear friction is considerably more complex than that of conventional friction [4, 5], the ACI 318-14 provision [6] simply considers that applied shear is mostly transferred by the resistance generated from the friction between the two sliding faces and a clamping force. The clamping force is induced by the transverse reinforcement crossing the interfaces. To calculate the clamping force, the stress of the transverse reinforcement is assumed to have reached its yield point. Therefore, the shear friction strength of concrete interfaces calculated using the equations of the code provisions [6, 7] increases in proportion to the clamping force which is commonly expressed as $\rho_{vf} f_y$, where ρ_{vf} and f_y are the ratio and yield strength of the interface reinforcing bars, respectively. However, Harries et al. [4] revealed that the stress in a high-strength steel reinforcement (with a yield strength of approximately 700 MPa) is lower than its yield strength at the ultimate state of concrete interfaces. Kwon et al. [8] examined code safety through comparisons with test results taken from 103 push-off specimens with monolithic interfaces. They concluded that the ACI 318-14 and AASHTO equations yield significant underestimations, whereas the overestimations of AASHTO equation are also frequently observed as $\rho_{vf} f_y$ is less than 8 MPa. In particular, the underestimation and disagreement owing to the use of the AASHTO equation are increased for the interface with smooth construction joints [9]. Overall, code equations that are empirically formulated using test data collected under a narrow range of influencing parameters do not sufficiently capture the mechanical diversity of the shear friction capacity of concrete interfaces with different concrete casting times.

Concrete interfaces frequently have a construction joint between the precast element and the cast-in-place concrete or at the surface formed by placing one layer of concrete on an existing layer of hardened concrete. When shear is applied to construction joints, the aggregate interlocking action and tensile resistance of concrete are insignificant along the interfacial plane. Hence, a lower shear friction resistance is inevitable along the construction joints than along the monolithic interfaces with or without initial cracks. However, many of the empirical equations [4, 5, 10–13] used to estimate shear friction strength have been proposed for monolithic interface, based on different experimental programs and the shear friction action associated with the truss model. Thus, test data and analytical approaches for construction joints are relatively insufficient. Code provisions [6, 7] specify that compared with that of monolithic interfaces, the coefficient of friction (μ) must be approximately 30% lower for smooth construction joints and approximately 60% lower for rough construction joints. However, there is no explicit experimental or analytical validation of this requirement.

The *fib* 2010 [14] provision specifies a 16.7% higher value of μ for rough construction joints than for smooth construction joints. Mattock [15] reported that the shear transfer due to concrete cohesion is considerably reduced in construction joints compared with the shear transfer that develops along monolithic interfaces in concrete. Santos and Júlio [16] pointed out that the roughness of the concrete substrate should be considered in the design expressions in the form of the coefficients of cohesion and/or friction because the bond strength of concrete-to-to interfaces is significantly affected by their substrate state. However, the cohesion and frictional coefficient of concrete in construction joints are still insufficiently interpreted, particularly for high-strength concrete with smooth surfaces. Moreover, the shear friction strength at overreinforced construction joints needs to be appropriately limited to avoid concrete crushing failure before the transverse reinforcement yield is reached. Most of the code equations do not provide an explicit validation for the upper limit or safety evaluation. Thus, the safety and rationality evaluations of the code equations are quite unsatisfactory for rough and smooth construction joints, although such evaluations for monolithic interfaces have been extensively performed in previous studies [3, 11, 15].

This study determines the cohesion and frictional coefficients of concrete at smooth and rough construction joints using a mechanical approach derived from the upper-bound theorem of concrete plasticity. The upper limits of the shear friction strength are derived from the state of concrete crushing failure limit on the strut-and-tie action along the construction joints to avoid overestimating the shear transfer capacity of a transverse reinforcement with a high clamping force. The reliability and limitation of the code equations [6, 7, 14] used to determine the shear friction strength of construction joints are also examined through comparisons with the experimental data compiled from different sources. Then, a parametric study is conducted using the proposed model, the AASHTO equation, and the results from the collected database to evaluate the effect of different parameters on the shear friction capacity of construction joints.

2. Database of Push-Off Specimens with Construction Joints

A total of 207 push-off specimens (including 133 rough construction joints, and 74 smooth construction joints) compiled from different sources in the literature [4, 5, 11, 17–25] were used to examine the reliability and safety of the code equations and mechanical equations with regard to the effect of the different parameters on the shear friction strength of the construction joints. The distribution of the different parameters in the database is shown in Figure 1. Although the roughness parameters, such as maximum peak-to-valley height, total roughness height, and maximum valley depth, influence the cohesion along the concrete interface [26], most of the literature does not provide the details on the substrate state of the interface. Thus, in the database, an interface with only a steel-brushing treatment is classified as a smooth construction joint, whereas an interface intentionally treated with sand blast with the full amplitude above approximately 1.5 mm is classified as a rough construction joint, with reference to the surface roughness classification specified in *fib* 2010 [14].

The test data available for smooth construction joints are relatively limited. All the specimens included in the database were reported to have failed in shear friction owing to a major crack along the interfacial plane. Only a few specimens had no transverse reinforcement crossing the interface. Most of the specimens with smooth construction joints were made of concrete with a high compressive strength (exceeding 55 MPa), whereas the compressive strength (f_c') of the concrete specimens with rough construction joints ranged between 12 MPa and 100 MPa. The clamping stress induced by the transverse reinforcement, which can be expressed as $\rho_{vf} f_y$, varied between 1.51 MPa and 6.37 MPa for smooth construction joints and between 1.40 MPa and 12.29 MPa for rough construction joints, where ρ_{vf} and f_y are the ratio and yield strength of the transverse reinforcement, respectively. The inclination (θ_s) of the transverse reinforcement to the interfacial plane varied between 45° and 90°. Most specimens with rough construction joints were tested with no normal stresses (σ_x) externally applied to the interface. Six rough construction joints were tested under additional applied tensile stresses ranging between $-0.04\ f_c'$ and $-0.1\ f_c'$. For the smooth construction joints subjected to an additional normal compressive stress, σ_x/f_c' was fixed at 0.15. Compressive and tensile stresses are denoted by the symbols (+) and (−), respectively.

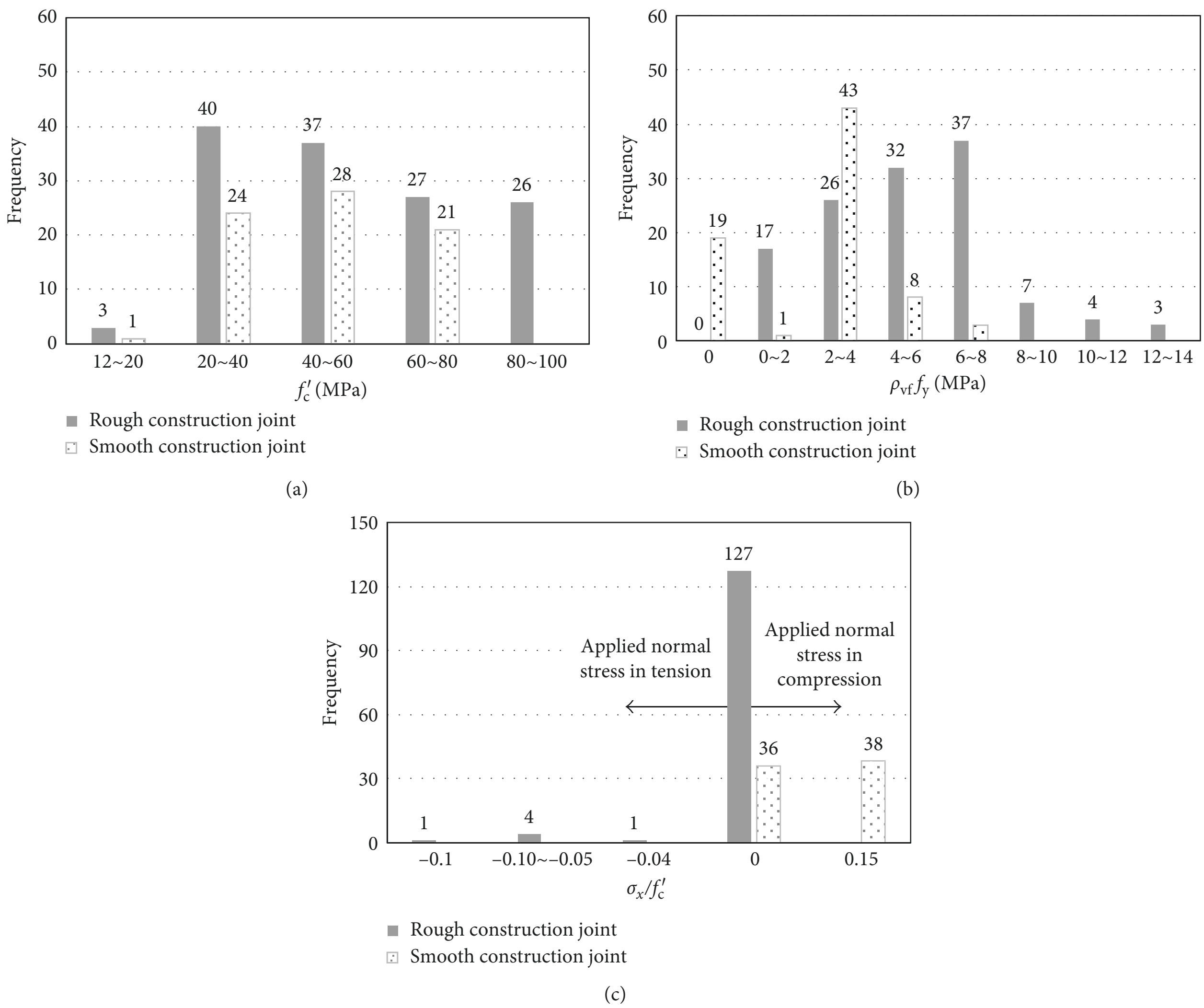

FIGURE 1: Distribution of different parameters in the 207 push-off specimens with construction joints: (a) compressive strength of concrete (f'_c); (b) clamping stress provided by transverse reinforcement ($\rho_{vf} f_y$); (c) ratio of applied normal stresses (σ_x) to f'_c.

3. Shear Friction Strength Models

Most empirical equations [4, 5, 10–13] for shear friction strength were fitted to a monolithic interface. Mattock [15] derived an experimental constant to determine the shear transfer of concrete in his empirical shear friction model for a monolithic normal-weight concrete interface. This constant was $0.1 f'_c$. However, the constant was fixed at 2.76 MPa for a rough construction joint. No fitting data or explanation for smooth construction joints is available in the empirical model developed by Mattock. Therefore, this examination of the shear friction design for construction joints focuses on the code equations and mechanical models.

3.1. ACI 318-14 Equation. The ACI 318-14 [6] provision specifies that the shear friction strength ($\tau_n = V_n/A_c$) of normal-weight concrete interfaces, based on the shear friction theory, is

$$\tau_n = \frac{V_n}{A_c} = \rho_{vf} f_y (\mu \sin\theta_s + \cos\theta_s), \quad (1)$$

$$\tau_n \le \min(0.2 f'_c, 3.3 + 0.08 f'_c, 11) \text{ (in MPa)} \quad \text{for rough construction joints,} \quad (2a)$$

$$\tau_n \le \min(0.2 f'_c, 5.5) \text{ (in MPa)} \quad \text{for smooth construction joints,} \quad (2b)$$

where V_n is the shear friction capacity, A_c is the section area of the interfacial plane, $\mu = (\tan\phi')$ is the coefficient of friction, and ϕ' is the friction angle of the concrete along the construction joint. The value of f_y is limited to 420 MPa to avoid the overestimation of the shear transfer capacity for overreinforcement or high-strength steel reinforcement. An upper limit for τ_n is imposed as a function of the concrete shear resistance, although the shear transfer capacity of concrete is ignored in calculating the shear friction strength of the interfacial plane. The increase in the shear friction

Table 1: Comparison of cohesion and frictional coefficients of concrete in each model.

Model	Cohesion		Coefficient of friction	
	Rough joint	Smooth joint	Rough joint	Smooth joint
ACI 318-14	Ignored		1.0	0.6
AASHTO	1.66 MPa	0.52 MPa	1.0	0.6
fib 2010	$0.10\ (f_c')^{1/3}$	0	0.7	0.6
This study	$0.27\ (f_c')^{0.65}$	$0.11\ (f_c')^{0.65}$	0.95	0.64

resistance due to the applied compressive stresses is not considered in (1), whereas the applied tensile stresses require an additional transverse reinforcement at the interfacial plane. The amount of transverse reinforcement can be determined by the equilibrium condition of force. The value of μ was set to be 1.0 and 0.6 for rough and smooth construction joints, respectively, as listed in Table 1. For the smooth construction joints, a reduced shear friction was accepted under the assumption that the shear force is primarily resisted by the dowel action of the transverse reinforcement. According to ((2a) and (2b)), the upper limit $[(\tau_n)_{\max}]$ is governed by $0.2f_c'$ when f_c' is less than 28 MPa, regardless of concrete joint type, whereas it is governed by $(3.3 + 0.08f_c')$ for the rough construction joints and 5.5 MPa for the smooth construction joints when f_c' is between 28 MPa and 100 MPa. Moreover, (1) and ((2a) and (2b)) imply that the clamping force induced by the transverse reinforcement becomes insignificant when $\rho_{vf}f_y$ exceeds a certain limit. For example, for interfaces made using concrete with f_c' ranging between 28 MPa and 100 MPa, the ratio of the reinforcement arranged perpendicular to the interfacial plane does not have to be greater than $(3.3 + 0.08f_c')/f_y$ for rough construction joints and $5.5/0.6f_y$ for smooth construction joints. This also implies that the ultimate frictional resistance provided by the transverse reinforcement depends on the roughness of the interfacial shear plane.

3.2. AASHTO Equation. The AASHTO equations [7] assume that interface shear resistance is directly proportional to the net normal clamping stress, based on a modified shear friction model that accounts for a contribution from cohesion and/or aggregate interlock. The AASHTO provision specifies the nominal τ_n of the interfacial plane as follows:

$$\begin{aligned} \tau_n &= c' + \mu\left(\rho_{vf}f_y + \sigma_x\right) = c' + \mu\sigma_{eq}, \\ \tau_n &\le \min\left(K_1 f_c', K_2\right), \end{aligned} \tag{3}$$

where c' is the concrete cohesion along the construction joint, for which the values are taken to be 0.52 MPa and 1.66 MPa for smooth and rough construction joints, respectively. The compressive stresses at the interfaces that develop from the transverse reinforcement and the externally applied normal compressive stresses are commonly equivalent to the summation of $\rho_{vf}f_y + \sigma_x$, which is then defined as the equivalent normal stress (σ_{eq}, in MPa) [27]. The experimental constants at the upper limits of τ_n, K_1 and K_2, are taken as 0.2 and 5.52 MPa, respectively, for smooth construction joints and 0.25 and 10.35 MPa, respectively, for rough construction joints. For smooth construction joints, the value of $(\tau_n)_{\max}$ specified in the AASHTO provision is identical to that in the ACI 318-14 equation. For rough construction joints, $(\tau_n)_{\max}$ is governed by $0.25f_c'$ when f_c' is less than 40 MPa, beyond which the upper limit increases to 10.35 MPa. This indicates that the AASHTO equation allows for a higher upper limit than the ACI 318-14 equation. The restriction for f_y is identical to ACI 318-14. All transverse reinforcing bars are assumed to be arranged perpendicular to the interface.

3.3. fib 2010 Equation. The *fib* 2010 model [14] has a similar structure to the AASHTO equation, but it considers interaction factor and dowel action of the transverse reinforcement. It is presented as follows:

$$\begin{aligned} \tau_n &= c_1\left(f_c'\right)^{1/3} + k_1\rho_{vf}f_{yd}\left(\mu\sin\theta_s + \cos\theta_s\right) + \mu\sigma_x \\ &\quad + k_2\rho_{vf}\sqrt{f_{yd}f_{cd}}, \\ \tau_n &\le \beta_c \nu f_{cd}, \\ \nu &= 0.55\left(\frac{30}{f_c'}\right)^{1/3} < 0.55, \end{aligned} \tag{4}$$

where c_1 is the factor to account for the aggregate interlock effect in concrete cohesion, k_1 and k_2 are the interaction factors for tensile force and flexural resistance generated in the transverse reinforcement, $f_{cd}\,(=f'/1.5)$ and $f_{yd}\,(=f_y/1.15)$ are the design compressive strength of concrete and design yield strength of reinforcement, β_c is the factor for the strength of the compression strut, and ν is the strength reduction factor of concrete. The values of c_1, k_1, k_2, and β_c are taken to be 0, 0.5, 1.1, and 0.4, respectively, for smooth construction joints. The corresponding values for rough construction joints are 0.1, 0.5, 0.9, and 0.5, respectively.

The *fib* 2010 considers that the main contributions to the sear resistance along the construction joints result from mechanical interlocking and adhesive bonding of concrete, friction due to external compression forces normal to the interface and clamping forces by reinforcement, and dowel action of reinforcement crossing the interface. The interlocking and adhesive bonding capacities of concrete depend on the surface roughness of the construction joints, assuming that the interlock effects at smooth construction joints are negligible. Compared with the cohesion capacity of the AASHTO equation, (4) yields a lower value, indicating that the interlocking and adhesive bonding capacities of concrete disappear compared to the other mechanisms of shear friction and dowel action. The upper limit of τ_n increases linearly with respect to f'_c. For example, the upper limit of τ_n for construction joints is calculated to be 3.67 MPa when f'_c is 20 MPa and 12.3 MPa when f'_c is 100 MPa. Compared with the value of μ in the ACI 318-14 and AASHTO provisions, the *fib* 2010 specifies the same value for smooth surfaces but a 30% lower value for rough surfaces, as listed in Table 1.

3.4. Mechanical Equations Derived Using Concrete Plasticity. Nielsen and Hoang [28] and Kwon et al. [8] showed that mechanism analysis based on the upper-bound theorem of concrete plasticity is a very promising method for describing the concrete cohesion and shear friction response of concrete monolithic interfaces or construction joints. They reported that concrete interfaces under direct shear and axial loads are usually separated into two rigid blocks at failure, as shown in Figure 2. One rigid block has two translational and rotational displacement components relative to the other rigid block. Thus, one rigid block can be assumed to rotate about an instantaneous center (IC). Similar to the failure mechanism of monolithic interfaces, the shear plane at failure along a construction joint can be regarded as a plane strain problem. Nielsen and Hoang [28] demonstrated that the angle between the relative displacement (δ) about an IC and the failure plane can be assumed to be equal to the frictional angle (ϕ') of concrete along construction joint. This angle can also be considered to be a constant value. Furthermore, tensile resistance in the concrete at construction joints is not usually expected, implying that the shear transfer of concrete along construction joints is entirely resisted by concrete cohesion. Concrete is regarded as a rigid perfectly plastic material that obeys a modified Coulomb failure criteria with effective compressive and tensile strengths. Therefore, if the tensile strength of concrete is ignored, the integrated model [8] for the shear friction strength of monolithic concrete interfaces can be modified for construction joints in the following form:

$$\tau_n = c' + \rho_{\mathrm{vf}} f_{\mathrm{y}} \frac{\cos(\theta_{\mathrm{s}} - \phi')}{\cos \phi'} + \sigma_x \tan \phi'. \quad (5)$$

For construction joints with transverse reinforcement of $\theta_{\mathrm{s}} = 90°$, (5) can be written as follows:

$$\tau_n = c' + (\rho_{\mathrm{vf}} f_{\mathrm{y}} + \sigma_x) \tan \phi' = c' + \sigma_{\mathrm{eq}} \tan \phi'. \quad (6)$$

Overall, the mechanical approach derived from the upper-bound theorem for the construction joints has the same format as shear friction theory. Equations (5) and (6) imply that the shear friction strength of nonreinforced construction joints without additional axial stresses is resisted only by the concrete cohesion along the interfacial failure plane. The AASHTO provision assumes the value of c' to be a constant, whereas *fib* 2010 [14] considers it to be a function of f'_c, as listed in Table 1. Nielsen and Hoang [28] reported that the value of c' depends on f'_c and the roughness along the interfacial plane. Dahl [29] conducted a regression analysis using a small set of test data obtained

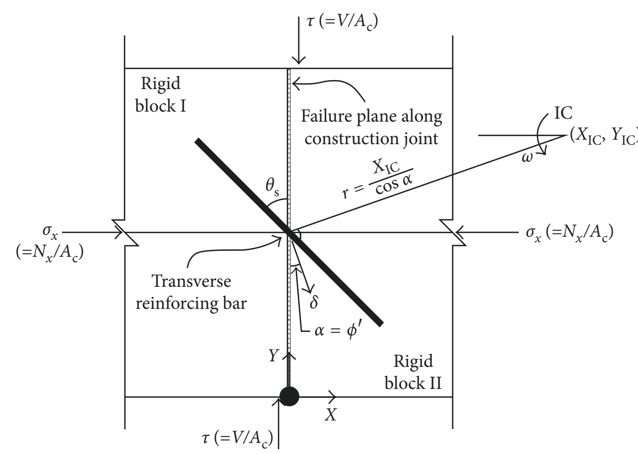

Figure 2: Idealized failure mechanism of the concrete interface with construction joints.

from four push-off specimens with smooth construction joints and showed that c' could be expressed as a function of $(f'_c)^{0.5}$. Experimental programs for determining the value of c' of nonreinforced construction joints are very scarce. If push-off specimens analysed by Choi et al. [30] and Hwang [18] are plotted to show c' for smooth and rough construction joints as a function of f'_c, the approximate relationship obtained is expressed as follows (Figure 3):

$$c' = 0.11 (f'_c)^{0.65} \quad \text{for smooth construction joints,} \quad (7a)$$

$$c' = 0.27 (f_c)^{0.65} \quad \text{for rough construction joints.} \quad (7b)$$

According to the code provisions, the enhanced cohesion on the rough surface due to mechanical treatment is estimated to be 320% for the AASHTO equation, whereas the *fib* 2010 neglects the cohesion capacity of smooth surface. Equation ((7a) and (7b)) shows that the rough surface has approximately 245% higher cohesion than the smooth surface. These equations yield a higher value for c' than the code equations, including *fib* 2010, but a lower value than the calculation of Nielsen and Hoang's equation [28]. Equation ((7a) and (7b)) would need to be further verified using the test data conducted under extensive range of f'_c values and for construction joints with the other surface impact treatments.

To determine the value of ϕ' using the test data, (5) is rearranged as follows:

$$\phi' = \tan^{-1}\left(\frac{\tau_n - c' - \rho_{\mathrm{vf}} f_{\mathrm{y}} \cos \theta_{\mathrm{s}}}{\rho_{\mathrm{vf}} f_{\mathrm{y}} \sin \theta_{\mathrm{s}} + \sigma_x}\right). \quad (8)$$

The calculated ϕ' values for the test data in the database commonly range between 29.4° and 44.5° for smooth construction joints and between 33.3° and 54.4° for rough construction joints. The average value of 32.8° ($\mu = 0.64$) for smooth construction joints and 43.5° ($\mu = 0.95$) for rough construction joints are within the typical ranges specified in *fib* model code 2010 [14].

Figure 4 plots the relationship between $\rho_{\mathrm{vf}} f_{\mathrm{y}}$ and the normalized shear friction strength (τ_n/f'_c) for rough construction joints. The normalized shear friction strength increases in proportion to $\rho_{\mathrm{vf}} f_{\mathrm{y}}$ up to a certain limit, beyond

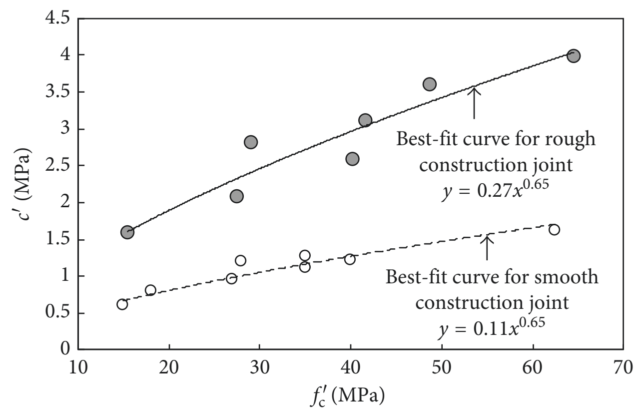

FIGURE 3: Relationship between c' and f_c' for the nonreinforced construction joints.

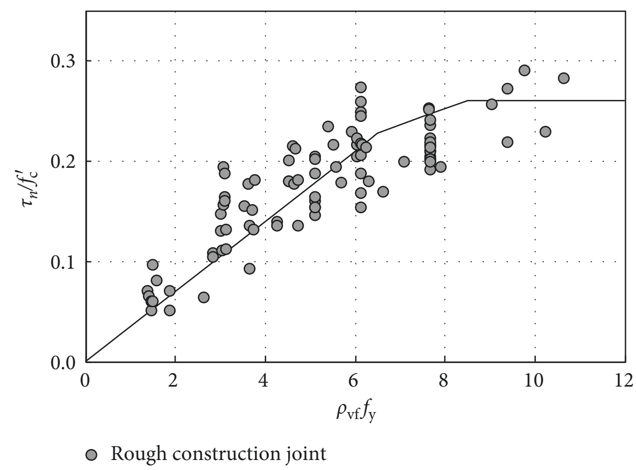

FIGURE 4: Relationship between τ_n/f_c' and $\rho_{vf}f_y$ for the construction joints.

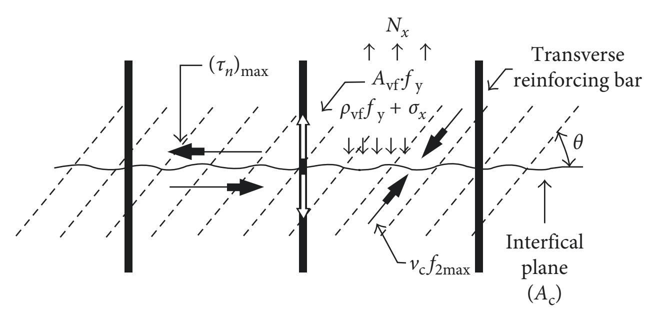

FIGURE 5: Idealized strut-and-tie action at the construction joints.

which the rate of increase gradually slows. This implies that the τ_n at the overreinforced construction joints is governed by the crushing of the concrete before the transverse reinforcement reaches its yield strength. Hence, τ_n needs to be limited to certain value in order to avoid the overestimation of the shear transfer of transverse reinforcement due to the precrushing failure of concrete. Figure 5 shows the idealized strut-and-tie action needed to transfer the applied shear along the construction joints [28] based on the concrete plasticity. The combined action of the shear force and clamping forces in the transverse reinforcement yields an inclined compressive force across the interfacial plane. The equilibrium condition of the forces yields the following relationship:

$$(\tau_n)_{max} \cdot A_c = \nu_c f_{2max} A_c \sin\theta \cos\theta, \tag{9}$$

where ν_c is the effectiveness factor of the concrete in compression to account for the assumed rigid plasticity, f_{2max} is the compressive strength of a cracked concrete strut under biaxial state of stresses, and $\theta(=(\pi/2)-\phi')$ is the inclination of the concrete struts appearing perpendicular to the frictional angle [31]. Kwon et al. [8] calculated the value of ν_c using the actual stress-strain curve of concrete and formulated it as follows:

$$\nu_c = 0.79 \exp\left[-0.03\left(\frac{f_c'}{f_{co}}\right)^{0.9}\left(\frac{\rho_o}{\rho_c}\right)^{1.6}\right], \tag{10}$$

where f_{co} (=10 MPa) and ρ_o (=2300 kg/m^3) are the reference values for the compressive strength and the unit weight of concrete, respectively. Belarbi and Hsu [32] tested concrete panels loaded under in-plane shear and proposed the following relationship between f_{2max} and f_c':

$$f_{2max} = \frac{0.9}{\sqrt{1+400\varepsilon_1}} f_c', \tag{11}$$

where ε_1 is the transverse tensile strain. For the cracked concrete along the interfacial plane, the value of ε_1 depends on the magnitude of f_c' and $\rho_{vf}f_y$. However, it is not easy task to establish the relationship of ε_1 and the influencing parameters in the concrete interface subjected to direct shear. For simplicity of the equation for $(\tau_n)_{max}$, the present study assumes that ε_1 would be approximately equivalent to the yield strain (≈0.002) of the mild transverse reinforcement. Overall, the upper limit of the shear friction strength at the construction joints can be simply expressed as follows:

$$(\tau_n)_{max} = 0.67\nu_c f_c' \sin\phi' \cos\phi'. \tag{12}$$

Figure 6 shows the variation of $(\tau_n)_{max}/f_c'$ calculated using the code and the proposed equations according to f_c'. All the equations yield the same trend, that is, $(\tau_n)_{max}/f_c'$ decreases with the increase of f_c', implying that the increasing rate of the crushing strength of concrete under a biaxial stress state is not linearly proportional to f_c'. Rahal [33] empirically proposed the upper limit based on experimental results using normal- and high-strength concrete, indicating that $(\tau_n)_{max}/f_c'$ varies linearly from 0.31 to 0.22 when f_c' increases from 20 MPa to 100 MPa, regardless of the roughness of the concrete substrate along the interface. For smooth construction joints (Figure 6(a)), the ACI 318-14 and AASHTO equations have the same values of $(\tau_n)_{max}/f_c'$, producing lower values than rough construction joints when f_c' is greater than 28 MPa. That is, a higher rate of decrease in $(\tau_n)_{max}/f_c'$ is observed in the smooth construction joints than in the rough construction joints. The developed equation has higher $(\tau_n)_{max}/f_c'$ values than the AASHTO and *fib* 2010 equations. For rough construction joints (Figure 6(b)), the ACI 318-14 equation exhibits a lower $(\tau_n)_{max}$ than the other equations when f_c' is lower than

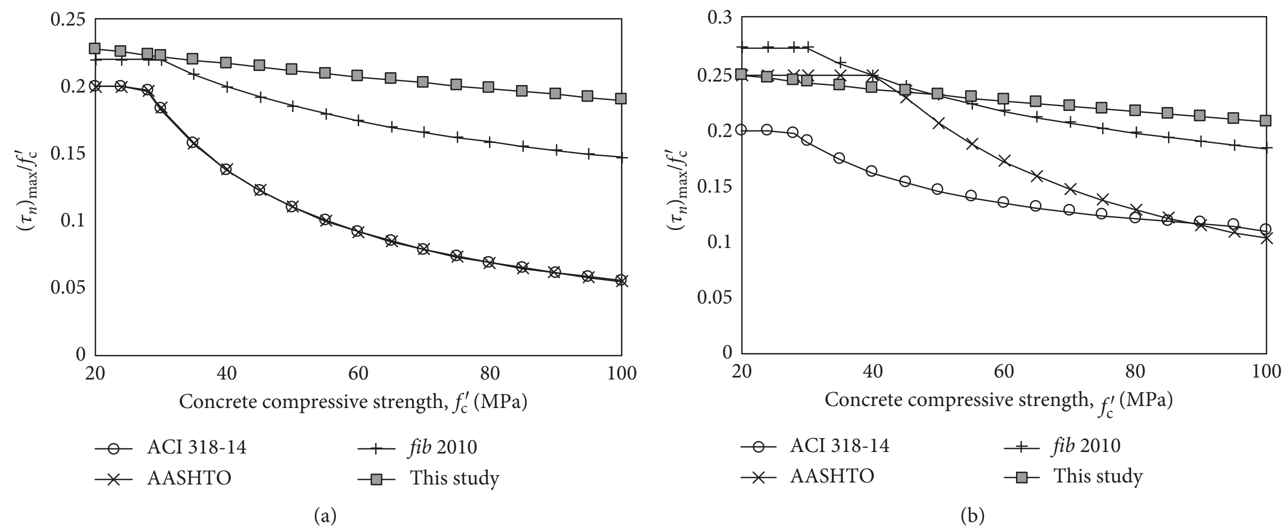

Figure 6: Comparisons of $(\tau_n)_{max}$ in the code and proposed models: (a) smooth construction joints; (b) rough construction joints.

90 MPa. The value of $(\tau_n)_{max}/f'_c$ calculated using the AASHTO equation remains constant at 0.25 up to an f'_c of 50 MPa, beyond which the value decreases rapidly. The value of $(\tau_n)_{max}/f'_c$ calculated using the *fib* 2010 equation also shows similar trend to the AASHTO equation but yields higher level than the other models when f'_c is less than 40 MPa. The developed equation has a higher $(\tau_n)_{max}/f'_c$ value for rough construction joints than for smooth construction joints, resulting in lower values than the *fib* 2010 equation when f'_c is lower than 50 MPa.

4. Comparison of Prediction Models and Test Results

4.1. Statistical Comparisons. Figure 7 shows comparisons between the measured shear friction strength of the push-off specimens with construction joints in the database and the predictions made by the code and developed equations. Note that any strength reduction factors are not considered in calculating shear friction strength using code equations and proposed model. Table 2 lists the statistical values for the mean (γ_m), standard deviation (γ_s), and coefficient of variation (γ_v) of the ratios [$\gamma = (\tau_n)_{Exp.}/(\tau_n)_{Pre.}$] between the experimental and predicted shear friction strengths. If $\gamma > 1$, the prediction model is conservative. Considering that various sources of test data may have different geometrical dimensions, material properties, and test arrangements, the 5% ($\gamma_{5\%}$) and 95% ($\gamma_{95\%}$) fractiles in all the tests are employed for evaluating the reliability of the prediction equations. The 5% and 95% fractiles are calculated from statistics as follows [34]:

$$\gamma_{5\%} = \gamma_m - R_0\gamma_s,$$
$$\gamma_{95\%} = \gamma_m + R_0\gamma_s. \qquad (13)$$

The coefficient, R_0, depends on the number (n) of test data samples used to compute the average and standard deviation. Because the values of R_0 range from 1.645 for n more than 120, to 2.010 for n of 40, and to 2.568 for n of 10, R_0 can be calculated from the interpolation of these values. The specimens without transverse reinforcement were excluded from the comparisons made using the ACI 318-14 equation because the code equation neglects concrete cohesion. The significant findings derived from the comparisons are discussed below.

The ACI 318-14 equation (Figure 7(a)) considerably underestimates the shear friction strength of reinforced smooth construction joints, which results in very high values of γ_m and $\gamma_{95\%}$. The values exceed 3.15 and 7.29, respectively. This is because the predictions do not consider concrete shear transfer by cohesion and are governed by the upper limit of τ_n when $\sigma_{vf} f_y$ is greater than approximately 8.7 MPa. For rough construction joints, the ACI 318-14 equation is still very conservative, yielding a high value of $\gamma_{95\%}$ exceeding 3.95, although a few unsafe data points are observed and γ_m decreases to 2.16. Large scattering of the data for the γ value is observed in the ACI 318-14 equations, resulting in considerably high γ_s values of 2.23 and 1.13 for smooth and rough construction joints, respectively. The AASHTO equation also provides underestimated results (Figure 7(b)) for smooth construction joints, although a few overestimated data points are observed when σ_{eq} is greater than approximately 11 MPa. The values of γ_m and γ_s obtained using the AASHTO equation are far smaller than those obtained using the ACI 318-14 equation. However, large scattering of the γ values is still observed in the AASHTO equation. Therefore, significant amounts of overestimated data points are observed for rough construction joints. The predictions obtained from the *fib* 2010 equation are frequently lower than the test results (Figure 7(c)), regardless of the roughness of the interfacial surface. The predictions yield lower values of γ_m and γ_s for smooth construction joints than the previous code equations. The unconservative trend of the *fib* 2010 equation for smooth construction joints is magnified when σ_{eq} is greater than approximately 11 MPa. The *fib* 2010 equation for rough construction joints has higher γ_m and γ_s values than the AASHTO equation. The predictions of the proposed model agree more closely with the test results (Figure 7(d)),

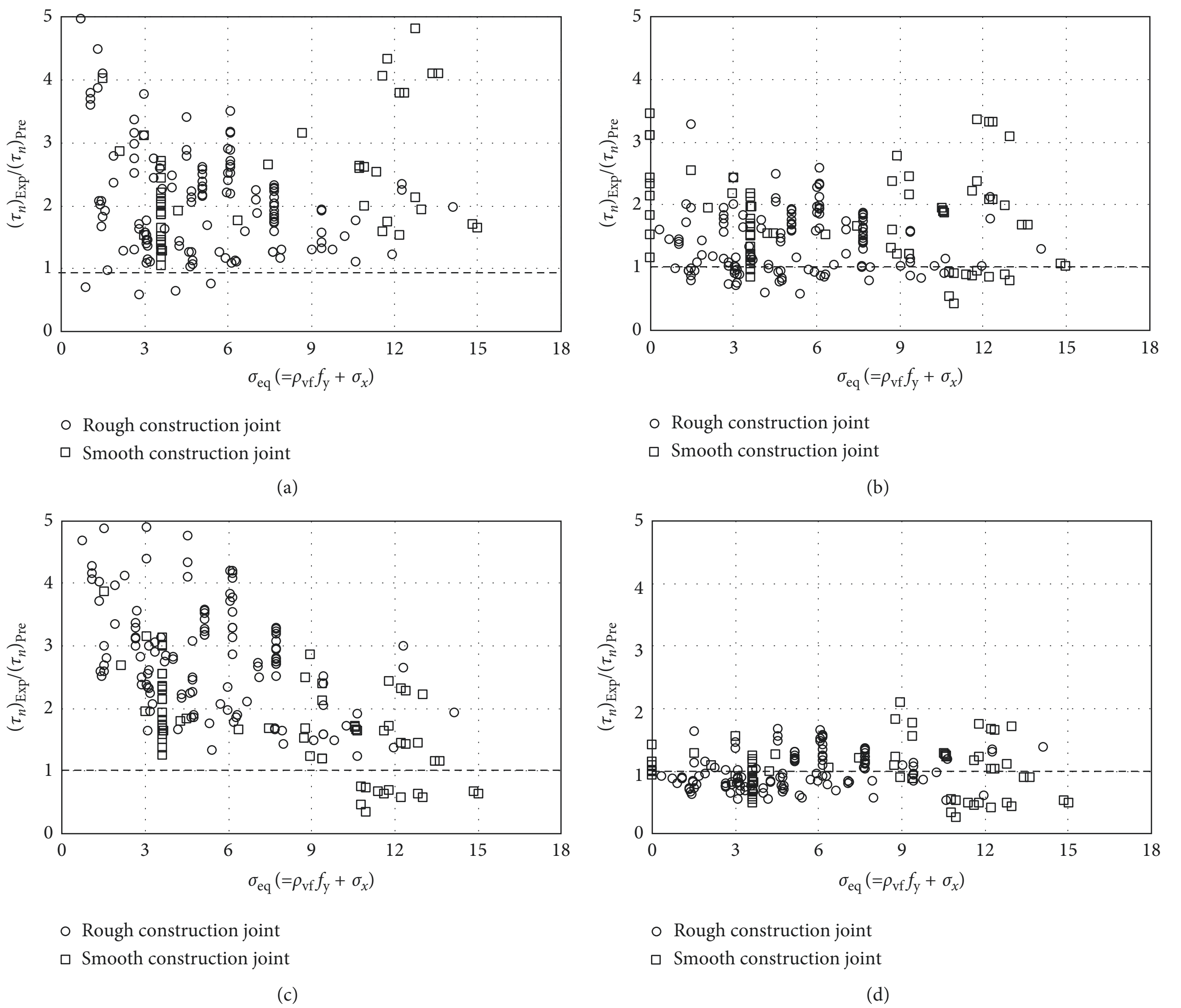

Figure 7: Comparisons of the measured and predicted shear friction strengths: (a) ACI 318-14 equation; (b) AASHTO equation; (c) *fib* 2010 equation; (d) this study.

Table 2: Statistical comparison of measured and predicted shear friction strengths.

Interface type	Statistical value	Proposer			
		ACI 318-14	AASHTO	*fib* 2010	This study
Smooth construction joint	γ_{m}	3.15	1.80	1.73	0.99
	γ_{s}	2.23	0.87	0.76	0.39
	γ_{v}	0.71	0.48	0.44	0.39
	$\gamma_{5\%}$	NA	0.18	0.31	0.27
	$\gamma_{95\%}$	7.29	3.42	3.14	1.72
Rough construction joint	γ_{m}	2.16	1.41	2.99	1.00
	γ_{s}	1.13	0.49	1.35	0.28
	γ_{v}	0.52	0.35	0.45	0.28
	$\gamma_{5\%}$	0.36	0.63	0.84	0.55
	$\gamma_{95\%}$	3.95	2.20	5.14	1.44
Total	γ_{m}	**2.46**	**1.56**	**2.56**	**1.01**
	γ_{s}	**1.64**	**0.68**	**1.33**	**0.32**
	γ_{v}	**0.67**	**0.44**	**0.52**	**0.32**
	$\gamma_{5\%}$	**NA**	**0.43**	**0.38**	**0.48**
	$\gamma_{95\%}$	**5.15**	**2.68**	**4.75**	**1.55**

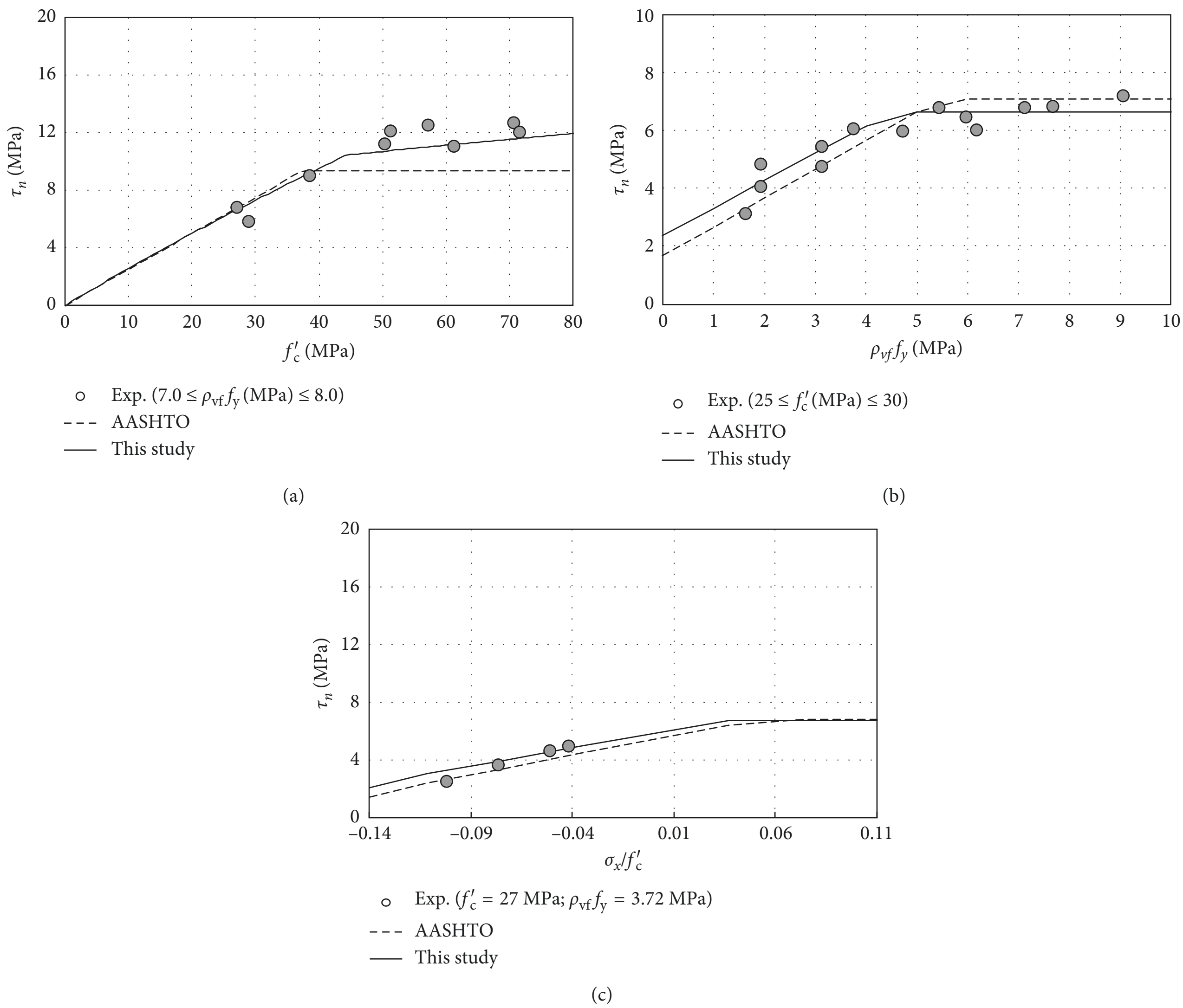

FIGURE 8: Effects of different parameters on the shear friction strength of construction joints: (a) compressive strength of concrete (f'_c); (b) clamping stress provided by transverse reinforcement ($\rho_{vf} f_y$); (c) ratio of applied normal stresses (σ_x) to f'_c.

exhibiting the lowest scatter value of γ according to the variation of ρ_{eq}. The values for γ_m and γ_s are 0.99 and 0.39, respectively, for smooth construction joints and 1.00 and 0.28, respectively, for rough construction joints. The overall values of γ_m, γ_s, and γ_v for the complete dataset are 1.01, 0.32, and 0.32, respectively, indicating smaller deviation in the proposed model than in the code equations when the shear friction strength of construction joints is predicted. Meanwhile, the proposed model exhibits more unconservative results than code equations, especially for construction joints with σ_{eq} exceeding 11 MPa. Thus, the proposed model needs to be further adjusted to incorporate the strength reduction factor considering the values of $\gamma_{95\%}$ and $\gamma_{5\%}$ to reduce the unconservative estimation of shear friction strength.

4.2. Verification of Primary Influencing Parameters. The influence of the primary parameters on the shear friction strength of the rough construction joints is studied using the proposed model and the AASHTO equation, as well as appropriate experimental results available in the database. To examine whether the code provisions reasonably consider the influencing parameters, the AASHTO equation with lower γ_s and γ_v values than the ACI 318-14 and *fib* 2010 equations is selected. In the parametric study, one parameter is incrementally changed while the others are kept constant. However, because the test results in the database were collected from different sources, it would not be possible to strictly achieve this, so average values of the concrete and steel reinforcement properties are used.

Figure 8(a) shows the effect of f'_c on τ_n for rough construction joints without additionally applied normal stresses. The prediction obtained using the AASHTO equation increases in proportion to f'_c up to a certain limit, beyond which it remains constant. The AASHTO equation tends to underestimate the shear friction strength of rough construction joints for $f'_c > 50$ MPa. The proposed model shows a similar trend to the AASHTO equation, yet it has a higher threshold point. The threshold point of τ_n against f'_c varies according to σ_{eq}. The predictions of the proposed model exhibit a good correlation with the test results.

A similar trend for the effect of $\rho_{vf} f_y$ on τ_n for rough construction joints is observed in both equations (Figure 8(b)), indicating a bilinear relationship with a threshold point at a certain $\rho_{vf} f_y$. This trend is also verified by the test data. The proposed model exhibits slightly better accuracy than the AASHTO equation with respect to the experimental data, with $\rho_{vf} f_y$ exceeding approximately 6 MPa.

The effect of σ_x/f'_c on τ_n for rough construction joints with f'_c of 27 MPa and $\rho_{vf} f_y$ of 3.72 MPa is shown in Figure 8(c). There are no available data for rough construction joints subjected to an externally applied normal stress in compression, as shown in Figure 1. Both equations exhibit a very close relationship between σ_x/f'_c and τ_n, indicating that a further increase in τ_n is not expected when σ_x/f'_c is greater than a certain value. For the rough construction joints subjected to an additional tensile stress, the predictions obtained using both equations agree well with the test results.

5. Conclusions

This study develops rational approach and model for shear friction design of concrete interface with smooth and rough construction joints on the basis of the upper-bound theorem of concrete plasticity. The reliability and limitations of code equations and proposed models for determining the shear friction strength (τ_n) of construction joints are examined through comparisons with test data compiled from 207 push-off specimens with interfaces between concrete that was cast at different times. However, this study classified the surface roughness into two categories of smooth and rough construction joints. Hence, the code and proposed equations need to be further verified for construction joints treated with other impact methods. The effects of various parameters on the shear friction strength of construction joints are also investigated using test results and prediction models, including the AASHTO equation and a proposed one. The following conclusions may be drawn according to the results obtained using the code equations and the proposed model:

(1) The developed equation has a higher upper limit for τ_n than the other equations but yields a lower upper limit for rough construction joints than the *fib* 2010 equation for $f'_c < 50$ MPa. The ACI 318-14 equation gives a lower upper limit for τ_n for rough construction joints than the other equations when f'_c is lower than 90 MPa.

(2) The ACI 318-14 equation significantly underestimates the shear friction strength of reinforced construction joints. In addition, larger scattering of the γ value is obtained with the ACI 318-14 equation than with the other equations, resulting in very high standard deviation (γ_s) values of 2.23 and 1.13 for the ratios (γ) in the cases of smooth and rough construction joints, respectively.

(3) Large scattering of the γ value is also observed in the AASHTO equation, although the determined values of the mean (γ_m) and γ_s are considerably lower than those obtained using the ACI 318-14 equation.

(4) The predictions obtained using the *fib* 2010 equation frequently underestimate the test results, regardless of the roughness of the interfacial surface. The predictions yield lower values of γ_m and γ_s for smooth construction joints than the previous code equations. The unconservative trend of the *fib* 2010 equation for smooth construction joints is magnified when σ_{eq} is greater than approximately 11 MPa.

(5) The predictions of the proposed model agree well with the test results, indicating the lowest scatter value for γ. The values of γ_m and γ_s are 0.99 and 0.39, respectively, for smooth construction joints and 1.00 and 0.28, respectively, for rough construction joints. This results in overall values for γ_m and γ_s of 1.01 and 0.32, respectively, for the complete dataset.

(6) According to the proposed model, the values of the cohesion and coefficient of friction of concrete are determined as 0.11 $(f'_c)^{0.65}$ and 0.64, respectively, for smooth construction joints and 0.27 $(f'_c)^{0.65}$ and 0.95, respectively, for rough construction joints.

Notation

A_c: Section area of interfacial failure plane
A_{vf}: Area of transverse reinforcement crossing interfacial failure plane
c': Cohesion of concrete along construction joints
c_1: Factor to account for roughness of interfacial plane in concrete cohesion
f_{2max}: Compressive strength of cracked concrete under biaxial stress
f'_c: Compressive strength of concrete
f_{co}: Reference value of the compressive strength of concrete (=10 MPa)
f_{te}: 5% fractile for tensile strength of concrete
f_y: Yield strength of transverse reinforcement
f_{cd}: Design compressive strength of concrete
f_{yd}: Design tensile strength of reinforcement
k_1: Interaction factors for tensile force activated in the reinforcement or the dowels
k_2: Interaction factors for flexural resistance activated in the reinforcement or the dowels
n: Number of test data
V_n: Direct shear force at interfacial failure plane
β_c: Factor for the strength of the compression strut
γ: Ratio between test results and predictions
$\gamma_{5\%}$: 5% fractile of γ values
$\gamma_{95\%}$: 95% fractile of γ values
γ_m: Mean of γ values
γ_s: Standard deviation of γ values
γ_v: Coefficient of variation of γ values
δ: Relative displacement about an instantaneous center
ε_1: Transverse tensile strain along interfacial plane

θ: Inclination of concrete strut relative to interfacial failure plane
θ_s: Inclination of transverse reinforcement relative to interfacial failure plane
μ: Coefficient of friction
ν: Strength reduction factor
ν_c: Effectiveness factor for concrete compressive strength
ρ_c: Unit weight of concrete
ρ_o: Reference value for unit weight of concrete ($=2300\,\text{kg/m}^3$)
ρ_{vf}: Transverse reinforcement ratio
σ_x: Axial stress normally applied to interfacial failure plane
σ_{eq}: Equivalent normal compressive stress ($=\rho_{vf} f_y + \sigma_x$)
τ_n: Shear friction strength
$(\tau_n)_{max}$: Upper limit for shear friction strength
ϕ': Friction angle of concrete along construction joint.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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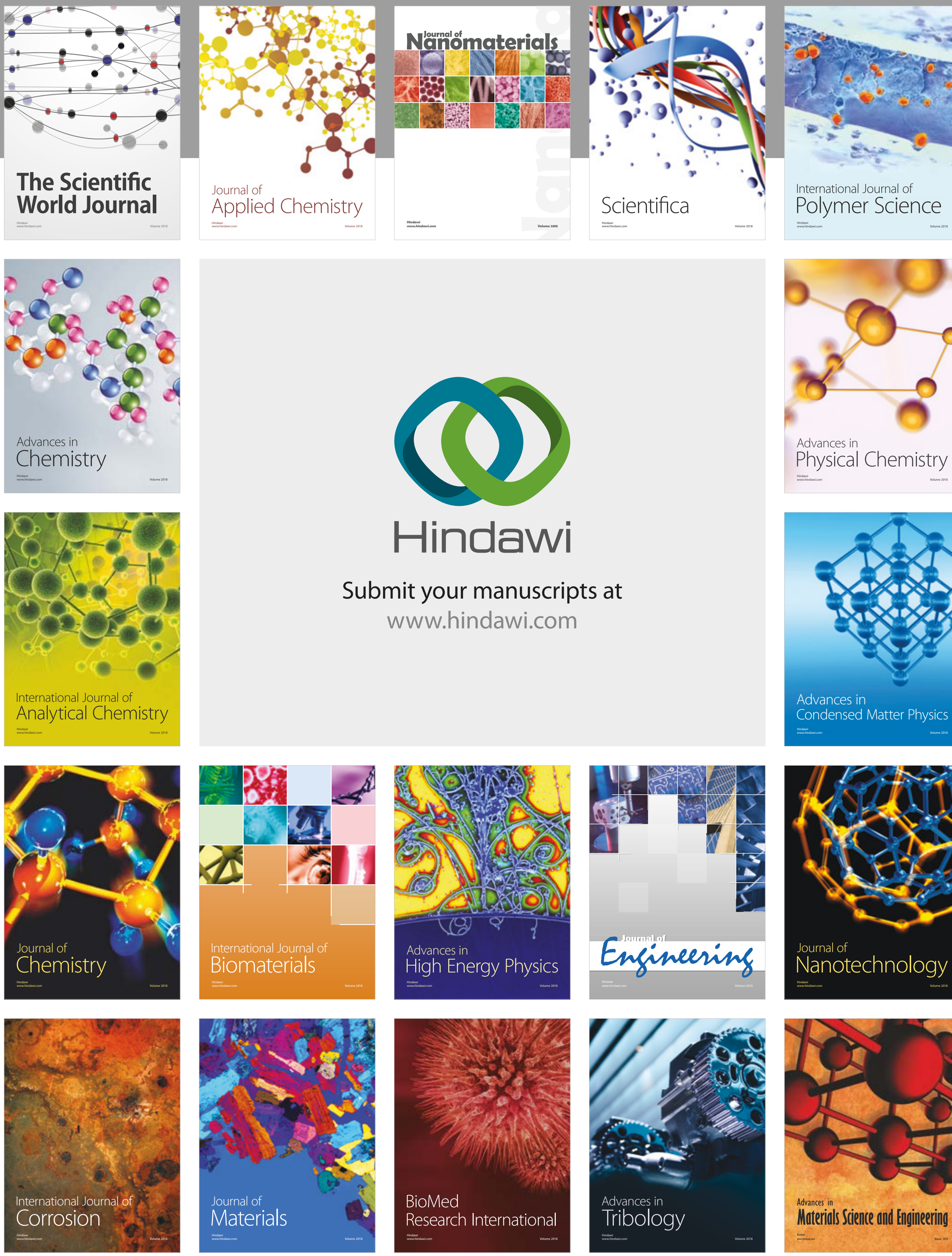
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