Structures 54 (2023) 1299–1311

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Influence of bond test methods on the bond performance between reinforcing bars and concrete

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A R T I C L E I N F O

Keywords:
Bond strength
Database
Beam test
Pull-out test
Unified model

A B S T R A C T

The bond strength between reinforcing bars and concrete is critical to structural performance for reinforced concrete structures. As bond strength is affected by the stress field, a beam test is recommended to evaluate the bond strength. However, the beam test is somewhat complicated and time-consuming compared to the pull-out test. To investigate the influence of test methods on the bond strength, databases including 598 existing beam test data and 197 existing pull-out test data were established. Based on existing beam test results and bond mechanism, a regression analysis was performed to propose the bond strength model. The proposed empirical equation can better meet the test phenomenon with less dispersion. Moreover, the empirical equation was directly applied to existing pull-out test results to evaluate the effect of test methods on bond strength. The results showed that the contributions of the development length-to-diameter ratio and restraint factor are consistent for the different test methods. However, the concrete stress field is significantly affected by the use of transverse bars and the test methods and results in various contributions of concrete strength. Besides, a unified bond strength equation was proposed using a strength conversion factor of concrete, which can be applied to beam and pull-out test specimens with $l_d/d_b \geqslant 7$. Additional tests were performed, which verified the prediction accuracy of the proposed unified model. Finally, based on the statistical analysis result, it can be inferred that the pull-out test method was still effective in evaluating the development length and bond strength in the concrete strength range of GB 50010–2010.

1. Introduction

The bond between reinforcing bars and concrete has been acknowledged as a critical mechanism for maintaining the integrity of reinforced concrete (RC) structures. Due to the complexity of bar bond behavior, experimental studies have investigated the bond strength and development length using four bond test methods: pull-out test, beam-end test, beam anchorage test, and lap splice test. In particular, the pull-out test has been widely used because of its ease of fabrication and simplicity of the test [1]. However, in pull-out test specimens, the tension force is applied to the reinforcing bar, while the compression force is developed in concrete. This stress state remarkably differs from most RC members, where the reinforcing bar and the surrounding concrete are tense. Thus, using pull-out test results to determine development length is inappropriate. It is not recommended in ACI 408R-03 [1]. On the other hand, the beam tests(beam-end, beam anchorage, and lap splice tests)can describe the bond behavior in actual structures. Thus, these tests are regarded as more reasonable bond test methods despite their test difficulty.

Current design codes, including ACI 408R-03 [1], ACI 318-19 [2], Eurocode 2 [3], and Model Code 2010 [4], specify development length based on existing experimental results obtained from the beam anchorage and lap splice tests. On the other hand, GB50010-2010 [5] applies pull-out test results to prescribe the development length. Thus, to verify the validity and feasibility of the design equation for development length derived from pull-out test results, the effect of test methods on the bond performance between reinforcing bars and concrete needs to be studied.

Although the discrepancy of stress fields between the pull-out test and actual structures is well known, the degree of influence of different stress states on the bond performance is inconclusive. Such differences caused by test methods can only be investigated through a systematic comparison between pull-out test results and other test results. However, most existing comparative studies use inconsistent test parameters

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https://doi.org/10.1016/j.istruc.2023.05.083
Received 28 January 2022; Received in revised form 5 February 2023; Accepted 22 May 2023

Table 1
Summary of beam test specimens in Database 1.

Author(s)(date) [Reference]	No. of tests	d_b (mm)	R_r	l_d/d_b	$c_{\min 1}/d_b$	K_{sv}	f_c' (MPa)	Test types
Chinn et al. (1955) [18]	32	9.5–35.8	–	9.3–32	0.7–2.3	–	21.8–51.6	lap splice
Chamberlin (1955) [19]	6	12.7	–	12	1–2	–	30.1–30.7	lap splice
Ferguson/Breen (1965) [20]	26	25.4–35.8	–	18–80	0.9–1.8	–	18–38.7	lap splice
Ferguson/Briceno (1969) [21]	20	25.4–35.8	–	23.4–60.3	0.6–1.5	–	16.9–30	lap splice
Seliem et al. (2009) [22]	31	15.9–35.8	–	24–70.4	1.1–3.2	–	28–70.3	lap splice
Hester et al. (1993) [23]	17	25.4	0.070–0.078	16–22.8	1.5–2	0–0.021	36.1–44.5	lap splice
Rezansoff et al. (1993) [24]	4	25.2–29.9	–	29.8–37.6	1	–	25.7–27.8	lap splice
Darwin et al. (1995) [25]	73	15.9–35.8	0.065–0.14	16–36	0.4–2.9	0–0.065	26.3–36.3	lap splice
Zuo/Darwin (1998) [12]	91	15.9–35.8	0.069–0.141	16–40	0.4–3	0–0.077	29.3–107.9	lap splice
Hamad (1999) [26]	8	25.4	–	12	1.5	–	52.3–76.7	lap splice
Azizanami et al. (1999) [27]	56	25.4–35.8	0.059–0.086	9.2–56.7	1–2	0–0.037	35–110.3	lap splice
Azizanami et al. (1993) [28]	13	25.4–35.8	–	9.2–56.8	1	–	35–104.2	lap splice
Hamad/Itani (1999) [29]	3	35.8	–	28.4–40.8	1	–	75.1–95.6	lap splice
Hamad/Mansour (1996) [30]	17	14–20	–	17.5–21.4	1–1.4	–	19.4–24.1	lap splice
Hwang et al. (1994) [31]	8	28.7	0.100	10.5	1	0–0.025	62.1–84	lap splice
Hwang et al. (1996) [32]	8	28.7	–	10.5–15.7	1.5–1.7	–	39.5–71.3	lap splice/ beam anchorage
Ferguson and Tompson (1962) [33]	26	9.5–35.8	–	18–40	0.9–3.3	–	16.4–41	beam anchorage
Mathey/Watstein (1961) [6]	14	12.7–25.4	0.088–0.096	7–34	1.5–3.5	0.047–0.112	24.1–30.9	beam anchorage
Kemp/Wilhelm (1979) [34]	12	35.8	–	11.4	0.7–2.1	–	26.4–30.6	beam-end
Ahlborn /DenHartigh (2002) [35]	23	19.1	–	8–16	2	–	37.9	beam-end
Darwin/Graham (1993) [36]	110	25.4	0.05–0.2	8.5–12	1.9–3.3	0–0.028	31.2–41.3	beam-end
Total	598	9.5–35.8	0.05–0.2	7–80	0.4–3.5	0–0.112	16.4–110.3	

(e.g., cover concrete thickness, transverse bars, bond length, *etc.*) for pull-out and beam anchorage test specimens [6–10]. Furthermore, it results in that the pull-out and beam test data cannot be analyzed under different conditions. In the study of Mathey et al. [6], the concrete cover used in pull-out and beam anchorage test specimens was inconsistent, and the bar occurred yield in part of pull-out test specimens. Thus, the effect of test methods on the bond strength could not be evaluated. Although Soretz [7] obtained the ratio between the bond strength in the pullout and the beam anchorage test, the test parameter was only the bar diameter (d_b). The development lengths used in the two types of specimens were inconsistent (i.e., bar development length was $5d_b$ and $10d_b$ in pull-out test specimens and beam anchorage test specimens, respectively.). Li [8] compared the bond performance between the pull-out and the beam anchorage test using test parameters of bar diameter, concrete cover, development length, and concrete strength. However, test results were not directly compared as inconsistent test parameters were used for counterpart specimens. Dancygier et al. [9] and Filho et al. [10] also used different test parameter settings for pull-out and beam test specimens.

The pull-out test generally considers a reinforcing bar with a relatively short development length (i.e., development length less than $15d_b$). On the other hand, the beam test database [11,12], which is used to develop average bond strength equations, excludes beam specimens with a development length of less than $15d_b$. Further, in the beam test database [13] used to define the average bond strength equation in Model Code 2010 [4], the number of beam specimens with a development length of less than $15d_b$ is about 15%. Thus, the bond performance of reinforcing bars in beam specimens with short development lengths cannot be accurately evaluated. Due to an insufficient understanding of the effect of test methods on the bond performance, the average bond strength equation obtained from beam test results cannot be directly applied to the pull-out test results and vice versa.

A unified model of bond strength addressing bond test methods was proposed in this study. To determine the main factors which affect bond strength, a regression analysis was performed using the existing beam test and pull-out test results. The bond mechanism between reinforcing bars and concrete was also discussed to understand variations in the effect of test parameters on the bond strength in each bond test method. Furthermore, a unified bond model was proposed, and some additional specimens(lap splice, beam-end, and pull-out tests) were performed to verify the prediction accuracy of the proposed unified model. Finally, the existing and proposed models were compared with existing test results to verify the validity and feasibility of the design equation for the development length derived from pull-out test results.

2. Databases of beam test and pull-out test

Three databases were established to compare and analyze the effect of test methods on the bond performance. Existing test results for beam test specimens (Database 1) and pull-out test specimens (Database 2) were established. The beam test specimens database (Database 1) was used for regression analysis to obtain a bond strength equation. Moreover, for direct comparison between test results, the beam test data (Database 3), having almost the same test parameter range as that of Database 2, was extracted from Database 1.

In existing empirical equations [1,11,12] based on regression analysis of lap splice test results, the development length (l_d) is not less than $15d_b$, addressing the minimum requirement in practice. Generally, pull-out test specimens use cubic concrete, and their development lengths are relatively short. To directly compare the effect of test methods on the bar bond strength, splice test specimens with $l_d/d_b \leq 15$ were also included in this study.

Previous studies [11,14,15] for database analysis have shown that bond properties are essentially the same for both lap splice test and beam anchorage test specimens. Based on a theoretical analysis, Tastani et al. [16] also reported that the discrepancy in bond performance between the splice and anchorage was insignificant. Thus, the beam database has no more controversial distinctions among lap splice, beam anchorage, and beam-end test specimens.

Current design codes specify that the splice length should be longer than the development length, addressing the proportion of lap splices. According to Cairns [17], the bond strength is not affected by the proportion of lap splices. GB 50100–2010 [4] also reports that the coefficient related to the proportion of lap splices can be used to satisfy the stiffness requirement. Thus, in this study, the effect of the lap splice ratio on the bond strength was not considered (i.e., $l_s = l_d$).

Based on the beam test data collected from previous studies [6,12,18–36], the following requirements of Database 1 were as follows: 1) Concrete compressive strength $f_c' \geq 10$ MPa; 2) When transverse bars were not used and the concrete cover was insufficient, the bond strength was not affected by the relative rib area of the reinforcing bar [36]. Thus, the relative rib area of rebars in only beam specimens with

Table 2
Summary of pull-out test specimens in Database 2.

Author(s)(date) [Reference]	No. of tests	d_b (mm)	R_r [a]	l_d/d_b	$c_{\min 1}/d_b$	K_{sv}	f_c' (MPa)
Xuning Niu [a] (2015) [37]	50	18–25	0.087	9.9–19.4	1.4–3.7	0–0.026	37.3–55.3
Yapeng Wang [a] (2009) [38]	21	14–22	0.087	10	1.6–4.9	0–0.040	12.9–34.5
Daling Mao [a] (2004) [39]	60	8–25	0.087	9.8–25	0.8–5.8	0–0.009	19.5–27.8
Xiaocheng Song [a] (2016) [40]	23	14–25	0.087	10.7	1.4–4.9	0–0.014	50–64.3
Youling Xu [a] (1990) [41]	35	16	0.087	8.1–18.8	0.9–4.2	0–0.035	14.2–35.8
Mathey (1961) [6]	8	12.7–25.4	–	7–21	4.5–9.5	–	22.3–33.5
Total	197	8–25.4	0.087	7–25	0.8–9.5	0–0.040	12.9–64.3

Notes: [a] The relative rib area was determined from the statistical result [42].

transverse bars was known; 3) Fresh concrete placed below rebars did not cause concrete casting position issues; and 4) Bond failure occurred before rebar yielding.

Table 1 shows the test parameters of 598 beam specimens (i.e., 379 specimens without transverse bars and 219 specimens with transverse bars) in Database 1. As seen in Table 1, the development length in the collected beam test data was $l_d/d_b \geq 7$. Thus, Database 2 was established from existing pull-out test specimens [6,37–41] to satisfy the following requirements: 1) $f_c' \geq 10$ MPa; 2) $l_d/d_b \geq 7$; 3) Fresh concrete placed below rebars did not cause concrete casting position issue; and 4) Bond failure occurred before rebar yielding.

Table 2 shows the test parameters of 197 pull-out test specimens (i.e., 113 specimens without transverse bars and 84 specimens with transverse bars). Based on the parameter range of Database 2, the following requirements were considered for database 3: 1) 12.9 MPa $\leq f_c' \leq$ 65.0 MPa; and 2) $7 \leq l_d/d_b \leq 25$. From Database 1, 333 beam specimens were extracted (i.e., 200 beam specimens without transverse bars and 133 beam specimens with transverse bars). Note that a development length of no longer than $5d_b$ was generally used in the majority of existing pull-out test specimens. For this reason, Database 2 was based mainly on pull-out test results in China.

In Tables 1 and 2, l_d is the bar development length; d_b is the rebar diameter;$c_{\min 1} = \min(c_{so}, c_{s1}, c_b)$; c_{so} is the side concrete cover for the reinforcing bar; c_{s1} is the half of the bar clear spacing; c_b is the bottom concrete cover for the reinforcing bar; f_c' is the concrete compressive strength based on 150 mm × 300 mm cylinders; R_r is the relative rib area of the reinforcing bar; and K_{sv} is the coefficient related to the confinement of transverse bars (refer to **Eq. (1)**). Beam test specimens in Database 1 used the compressive strength f_c' of 150 mm × 300 mm concrete cylinders. In contrast, most pull-out test specimens in Database 2 used the compressive strength f_{cu} of (150 mm)^3 cubes. According to Model Code 2010 [4], the cubic strength f_{cu} was converted to the cylindrical strength f_c'.

The wedging action of a reinforcing bar develops internal cracks along with the rebar, which increases the stress of transverse bars for confinement. However, the existing test results showed that the transverse bars rarely yielded, and the effect of the yield strength of transverse bars on bond strength was negligible [43]. Thus, the confinement of the transverse bars can be determined as follows:

$$\frac{Nn_1A_{sv,1}}{n_2\pi d_b l_d} = k_n\frac{A_{sv,1}}{\pi d_b s} = \frac{K_{sv}}{\pi} \tag{1}$$

Where N is the number of transverse bars within l_d; n_1 is the number of legs of a transverse bar on the splitting plane; n_2 is the number of bars being developed or spliced along the splitting plane; $A_{sv,1}$ is the cross-sectional area of the transverse bar; k_n is the ratio of n_1 to n_2; and s is the spacing of transverse bars ($=l_d$ / N).

3. Design provisions and empirical equations

3.1. Design provisions

In GB50010-2010 [5], the basic anchorage length of a reinforcing bar is defined as follows.

$$l_a = \zeta_a l_{ab} = \zeta_a \alpha \frac{f_y}{f_t} d_b \geqslant 200 \text{ mm} \tag{2}$$

where ζ_a is the coefficient of rebar properties ($=\gamma_1\gamma_2 \geqslant 0.6$); $\gamma_1 = 1.10$ for deformed bars with rebar diameter above 25 mm; γ_2 = coefficient of cover concrete thickness (=0.80 for $3d_b$ to 0.7 for $5d_b$); α is the coefficient of rebar geometry (=0.14 for deformed bars); and f_t is the concrete tensile strength (=0.91 MPa for C15 concrete to 2.22 MPa for C80 concrete). Note that lap splice length l_s is defined as $1.2l_a$ to $1.6l_a$ according to the area ratio of bar splices within $1.3l_s$. Considering the cut-off length (=the development length) of $1.2l_a$, an additional coefficient of 1.2 should be considered for beam specimens in Database 1 and 3 (i.e., $l_s = l_d = 1.2l_a$).

In ACI 318–19 [2], the development length of a reinforcing bar is defined as follows.

$$l_d = \frac{f_y d_b}{1.1\sqrt{f_c'}} \frac{\psi_t \psi_s}{(c_f + K_{ctr})/d_b} \geqslant 300 \text{ mm} \tag{3}$$

$$(c_f + K_{ctr})/d_b \leqslant 2.5 \tag{4}$$

$$c_f = c_{\min 1} + 0.5d_b = \min(c_{so}, c_{s1}, c_b) + 0.5d_b \tag{5}$$

$$K_{ctr} = 40A_{tr}/(sn_2) \tag{6}$$

Where A_{tr} is the total cross-sectional area of transverse bars within spacing s that cross the potential plane of splitting; ψ_t is the coefficient of fresh concrete below the reinforcing bars (=1.3 for fresh concrete thickness>300 mm, otherwise, 1.0); and ψ_s is the coefficient of the rebar diameter (=1.0 for d_b > 19 mm, otherwise, 0.8). When a lap splice is used, the lap splice length l_s is defined as $1.0l_d$ and $1.3l_d$ for Class A and Class B splice, respectively.

In Eurocode 2 [3], the development length of a reinforcing bar is defined as follows.

$$l_d = \alpha_2\alpha_3\frac{f_y d_b}{4\tau} \geqslant \frac{l_0}{1.5} \tag{7}$$

$$\tau = 2.25\eta_2 f_{ctd} = 2.25\eta_2\left[0.7\cdot 0.3\left(f_c' - 8\right)^{2/3}\right] \tag{8}$$

$$\alpha_2 = 0.7 \leqslant 1 - 0.15(c_{\min 1} - d_b)/d_b \leqslant 1.0 \tag{9}$$

$$\alpha_3 = 0.7 \leqslant 1 - k_a\left(\sum A_{tr} - 0.25A_s\right)\Big/A_s \leqslant 1.0 \tag{10}$$

Where $l_0 = \max\left\{0.45d_b f_y/(4\tau), 15d_b, 200 \text{ mm}\right\}$;$f_{ctd}$ is the concrete tensile strength [3]; k_a is the coefficient of the arrangement of transverse bars (=0 to 0.1); $\sum A_{tr}$ is the total cross-sectional area of transverse bars within the development length; A_s is the maximum cross-sectional area of rebar; and η_2 is the coefficient for rebar diameter $(=(132 - d_b)/100 \leqslant 1.0)$. The lap splice length l_s is defined as $1.0l_d$ to $1.5l_d$ according to the area ratio of spliced bars within $0.65l_d$.

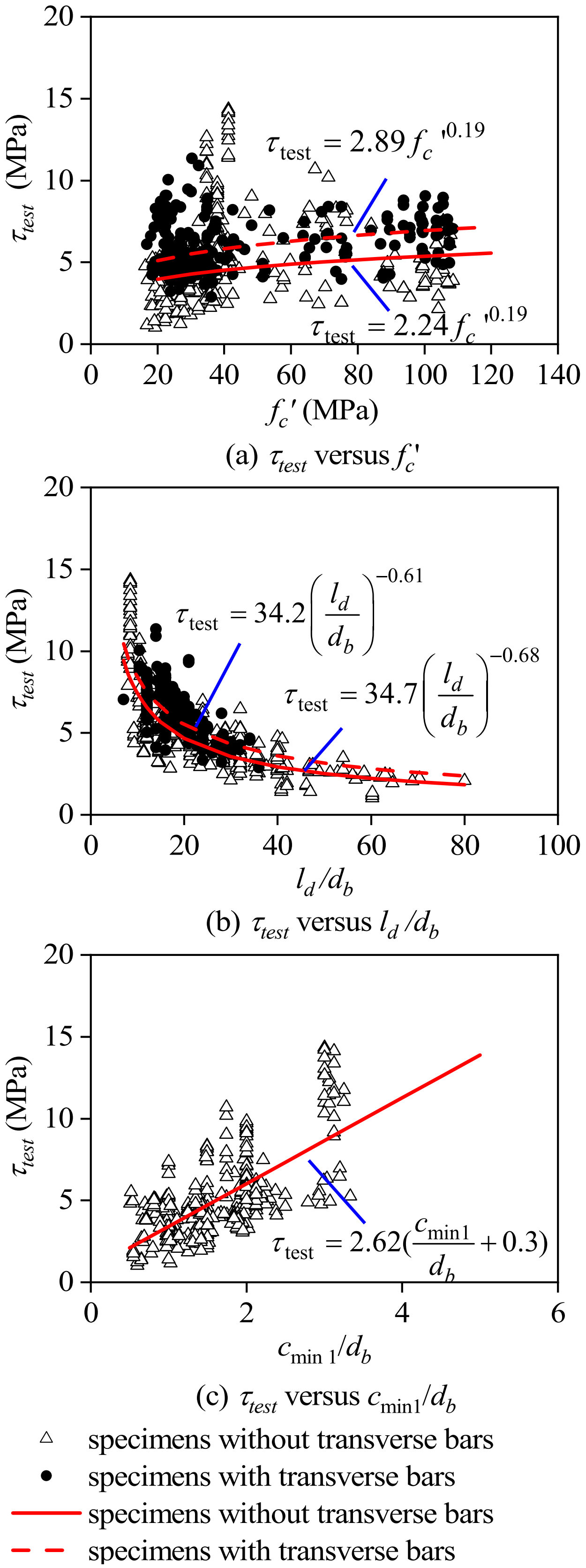

Fig. 1. Relationship between bond strength of Database 1 and test parameters.

3.2. Empirical equations

On the basis of pull-out test results, Xu [41] empirically proposed the bond strength (τ) of a reinforcing bar, which was adopted to develop the equation of GB50010-2010 [5].

$$\tau = \left(0.82 + 0.9\frac{d_b}{l_d}\right)\left(1.6 + 0.7\frac{c}{d_b} + 20\rho_{sv}\right)f_t \tag{11}$$

Where c is the minimum cover concrete thickness of the pull-out test specimen; and ρ_{sv} is the coefficient of transverse bars ($=A_{sv}/(c\cdot s)$). Note that values of $c = c_{\min 1}$ and $\rho_{sv} = k_n A_{sv,1}/(c\cdot s)$ were applied to the beam specimens in Databases 1 and 3 (refer to **Eq. (1)**).

In ACI 408R-03 [1], the development length of a reinforcing bar is defined as follows.

$$l_d = \frac{\left(f_y/\sqrt[4]{f'_c} - 57.4\omega\right)\psi_t\psi_s d_b}{1.83(c_a\omega + K_{atr})/d_b} \geqslant \max(300\text{ mm}, 16d_b) \tag{12}$$

$$(c_a\omega + K_{atr})/d_b \leqslant 4.0 \tag{13}$$

$$\omega = 0.1(c_{\max a}/c_{\min a}) + 0.9 \leqslant 1.25 \tag{14}$$

$$K_{atr} = 6.262\sqrt{f'_c}\, t_r t_d A_{tr}/(sn_2) \tag{15}$$

Where $c_a = c_{\min a} + d/2$; $c_{\max a} = \max(c_b, c_{sa})$; $c_{\min a} = \min(c_b, c_{sa})$; $c_{sa} = \min(c_{so}, c_{s1} + 6.4)$; t_r is the coefficient for the relative rib area ($=9.6R_r + 0.28 \leqslant 1.72$); and t_d is the coefficient for the effect of bar diameter on the stirrup restraint ($=0.03d_b + 0.22$). The lap splice length l_s is the same as l_d.

The bond strength f_{bd} of Model Code 2010 [4] was derived from the semi-empirical expression of **Eq. (16)** by *fib* TG4.5 [56], which was calibrated using over 800 beam anchorage test and splice test results.

$$f_s = 54\left(\frac{f'_c}{25}\right)^{0.25}\left(\frac{25}{d_b}\right)^{0.2}\left(\frac{l_d}{d_b}\right)^{0.55}\left[\left(\frac{c_{\min 1}}{d_b}\right)^{0.25}\left(\frac{c_{\max b}}{c_{\min 1}}\right)^{0.1} + k_m K_{sv}\right] \tag{16}$$

where $c_{\max b} = \max(c_{so}, c_{s1})$; $c_{\min 1}/d_b = 0.5$ to 3.5; $c_{\max}/c_{\min 1} = 1.0$ to 5.0; k_m is the coefficient of the arrangement of transverse bars ($=0$ to 12); and $K_{sv} \leqslant 0.05$ (refer to **Eq. (1)**).

To calculate the bond strength, rebar yield strength f_y in **Eqs. (2)**, **(3)**, and **(12)**was replaced with the rebar stress f_s. Assuming bond stress is uniform, the bond strength was defined as $\tau = f_s d_b/(4l_d)$.

In GB50010-2010 [5],

$$\tau = \frac{f_t}{0.56\zeta_a} \tag{17}$$

for pull-out test specimens.

$$\tau = \frac{f_t}{0.672\zeta_a} \tag{18}$$

for beam test specimens.

In ACI 318–19 [2],

$$\tau = \frac{0.275\sqrt{f'_c}(c_f + K_{ctr})}{\psi_t\psi_s d_b} \tag{19}$$

In ACI 408R-03 [1],

$$\tau = \sqrt[4]{f'_c}\left[14.35\omega\frac{d_b}{l_d} + \frac{0.458(c_a\omega + K_{atr})}{\psi_t\psi_s d_b}\right] \tag{20}$$

In Model Code 2010 [4],

$$\tau = 13.5\left(\frac{f'_c}{25}\right)^{0.25}\left(\frac{25}{d_b}\right)^{0.2}\left(\frac{l_d}{d_b}\right)^{-0.45}\left[\left(\frac{c_{\min 1}}{d_b}\right)^{0.25}\left(\frac{c_{\max}}{c_{\min 1}}\right)^{0.1} + k_m K_{sv}\right] \tag{21}$$

Table 3
COV of Eq. (22) in Database 1 according to the effective value of c_{si}.

Existence of k_c	$c_{si} = nc_{s1}$ $n = 1.0$	$n = 1.2$	$n = 1.4$	$n = 1.6$	$n = 1.8$	$n = 2.0$
With k_c	0.1427	0.1416	0.1416	0.1409	0.1417	0.1428
Without k_c	0.1529	0.1532	0.1542	0.1548	0.1560	0.1570

Notes: k_c is the coefficient related to the effect of concrete cover on the additional bond strength provided by transverse bars.

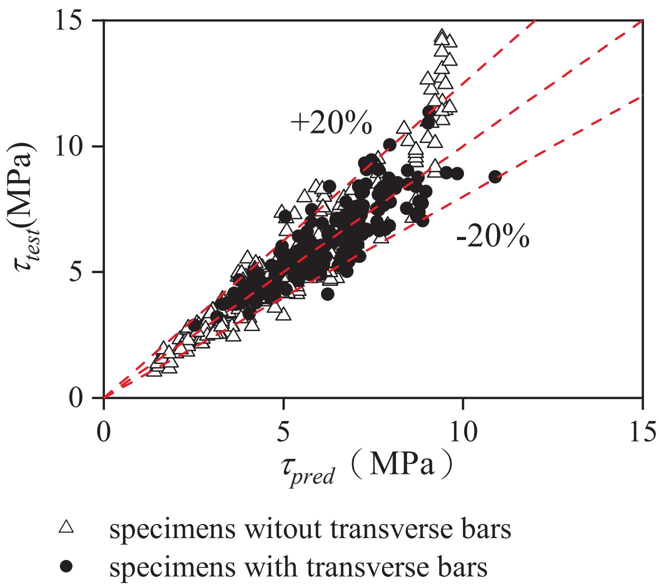

Fig. 2. Comparison of test results and predictions of Eq. (23) in Database 1.

4. Regression analysis based on Database 1

Previous studies [11,12,15] have shown that the bond strength is determined by the following factors: 1) concrete compressive strength; 2) bar development length-to-diameter ratio; 3) confinement of cover concrete; and 4) confinement of transverse bars. Therefore, for nonlinear regression analysis, the mathematical model of these factors should be determined first.

4.1. Concrete compressive strength

Fig. 1(a) shows that as the concrete compressive strength increases, the bar bond strength increases. Therefore, in this study, a factor of $f_c'^{\,a_1}$ was used to consider the effect of concrete strength on the bond strength.

4.2. Bar development length-to-diameter ratio

As the development length increases, its bond capacity also increases. However, the bond stress is not uniformly distributed along the development length. Thus, the average bond strength decreases with an increase in the relative development length [1]. As shown in Fig. 1(b), the influence of development length on the bond strength was more prominent for specimens with $l_d/d_b \leqslant 15$. When the database involved specimens with $l_d/d_b \leqslant 15$, the effect of development length on the bond strength should be fully reflected in the regression analysis. Therefore, a factor of $\tau = (l_d/d_b)^{a_2}$ was used to consider the effect of development length on the bond strength (Fig. 1(b)).

4.3. Confinement of cover concrete

According to Orangun et al. [11], Darwin et al. [25], and Model Code 2010 [4], the bond strength is significantly affected by the minimum concrete cover $c_{\min} = \min(c_{so}, c_{si}, c_b)$. As shown in Fig. 1(c), the bond strength increases with the minimum concrete cover $c_{\min}$ increase when splitting failures occur. Note that at the beginning of determining the form mathematics model, the effective value of the bar spacing c_{si} cannot be confirmed. The nominal minimum concrete cover $c_{\min 1} = \min(c_{so}, c_{s1}, c_b)$ was used in Fig. 1(c). Thus, a factor of $a_3 c_{\min}/d + a_4$ was used to consider the effect of the minimum concrete cover on the bond strength.

Unlike the side concrete cover c_{so} and the bottom concrete cover c_b, the value of the bar spacing c_{si} was differently defined in design codes and existing models. For example, ACI 318–19 [2] and Model Code 2010 [4] define $c_{si} = c_{s1} = c_s/2$ (where c_s is the bar spacing). Zuo and Darwin [12] proposed $c_{si} = 1.6c_{s1}$ and $c_{s1} + 6.4$ mm for beam specimens without and with transverse bars, respectively. ACI 408R-03 [1] adopted $c_{si} = c_{s1} + 6.4$ mm. Note that when the splitting failure occurs, the effective crack length is longer than the value of c_{s1}, so the effective value of c_{si} is greater than $c_s/2$ [14]. Thus, based on the approach of Zuo and Darwin [12], the effective bar spacing $c_{si} = nc_{s1} = 1.6c_{s1}$ was considered, showing minimal dispersion in the regression analysis (Table 3).

Further, as an increase of the value of $c_{\max}/c_{\min}$ would increase the bond strength, the factor of $(c_{\max}/c_{\min})^{a_5}$ was considered in this study. The maximum concrete cover $c_{\max}$ was defined as $\max(c_b, \min(c_{so}, c_{s1} + 6.4))$ in ACI 408R-03 [1] or $\max(c_{so}, c_{s1})$ in Model Code 2010 [4]. Based on the principle of minimal dispersion in the regression analysis of Database 1, $c_{\max} = \max(c_{so}, c_{si})$ was considered (i.e., Coefficient of Variation(COV) = 0.1439 for $c_{\max} = \max(c_{so}, c_{s1})$ and COV = 0. 1556 for $c_{\max} = \max(c_b, \min(c_{so}, c_{s1}))$) (refer to "**4.5 Proposed bar bond strength**").

4.4. Confinement of transverse bars

The use of transverse bars restrains the development of splitting cracks. As the transverse bar ratio increases, the splitting failure is changed to pull-out failure, which increases the bond strength at a certain level [11]. For this reason, current design codes [1–4] limit the maximum bond strength increased by the concrete cover and transverse bars. Furthermore, when splitting cracks occurs, the ring tensile stress in the concrete at splitting cracks is resisted by transverse bars. Thus, compared to the less-cover specimens with the same transverse bar, the thicker-cover specimens have less additional bond strength contributed by the transverse bar. Recent studies also have shown that the additional bond strength contributed by transverse bars is directly proportional to the cross-sectional area of the transverse bars and is inversely proportional to transverse bar spacing, longitudinal bar diameter, and concrete cover [45]. Therefore, when transverse bars were used, a factor of $k_c =$

Table 4
Test–prediction ratio for bond strength models in Database 1.

Beam specimens	GB50010-2010 (Eq.18) Mean	COV	ACI318-19 (Eq.19) Mean	COV	Eurocode 2 (Eq.8) Mean	COV	Background of GB (Eq.11) Mean	COV	ACI408-03 (Eq.20) Mean	COV	Background of MC 2010 (Eq.21) Mean	COV	Proposed Model (Eq.23) Mean	COV
All	1.36	0.359	1.19	0.362	1.45	0.530	0.75	0.289	1.03	0.250	1.01	0.178	1.00	0.143
without stirrups	1.16	0.410	1.21	0.391	1.37	0.599	0.74	0.333	1.07	0.282	1.02	0.196	1.00	0.155
with stirrups	1.53	0.248	1.17	0.304	1.60	0.411	0.76	0.196	0.97	0.137	1.00	0.140	1.01	0.118

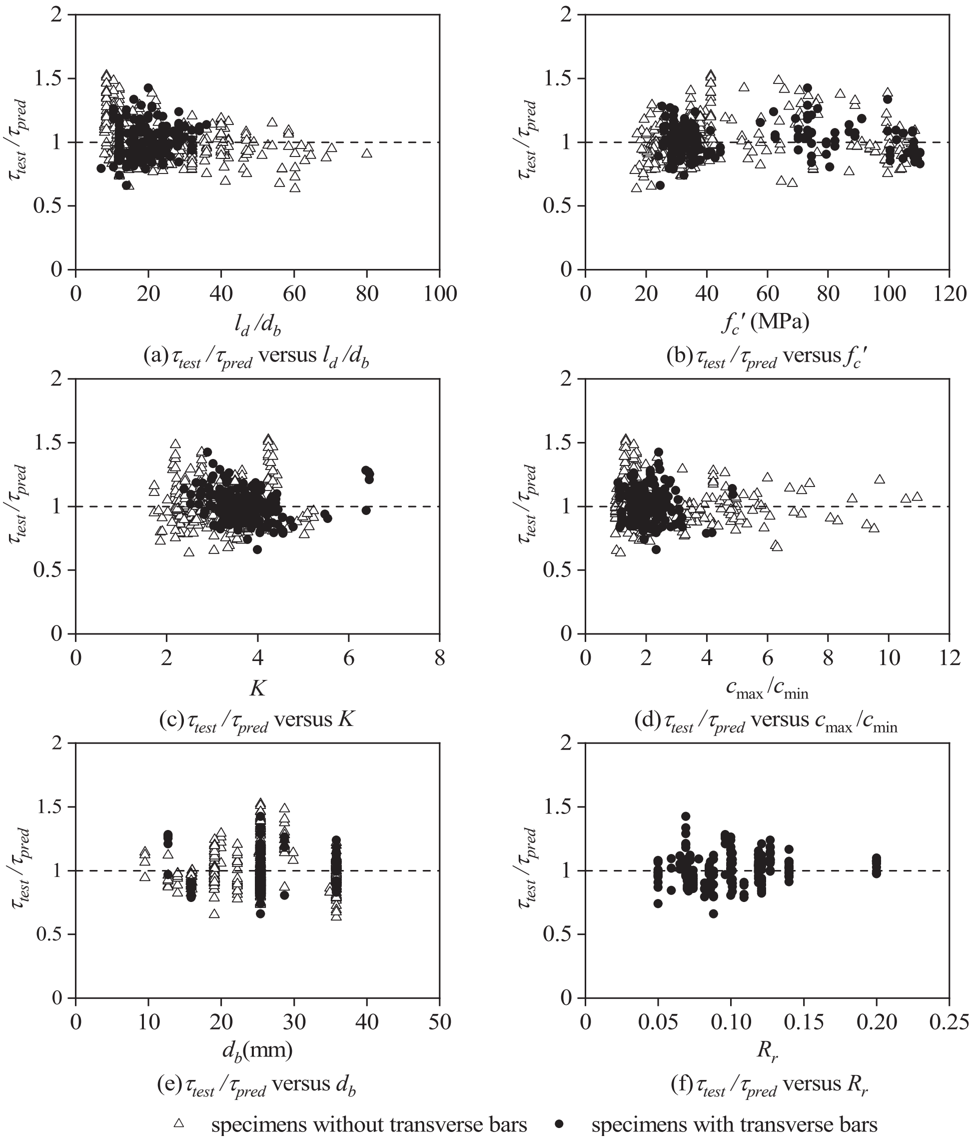

Fig. 3. Variation of test–prediction ratio of Eq. (23) versus test parameters in Database 1.

Table 5
Test–prediction ratio for bond strength models in Database 3.

Beam specimens	GB50010-2010 (Eq.18)		ACI318-19 (Eq.19)		Eurocode 2 (Eq.8)		Background of GB (Eq.11)		ACI408-03 (Eq.20)		Background of MC 2010 (Eq.21)		Proposed Model (Eq.23)	
	Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV	Mean	COV
All	1.61	0.261	1.39	0.311	1.84	0.395	0.85	0.222	1.07	0.240	1.02	0.195	1.00	0.145
without stirrups	1.57	0.290	1.46	0.309	1.82	0.441	0.88	0.234	1.12	0.263	1.06	0.215	1.00	0.164
with stirrups	1.68	0.214	1.28	0.296	1.86	0.326	0.80	0.182	0.98	0.149	0.96	0.131	0.99	0.111

$(c_{\min}/d_b)^{a_7}$ was applied to consider the effect of concrete cover on the additional bond strength provided by transverse bars (Table 3).

When transverse bars are not used, and the concrete cover is insufficient, bond strength is not affected by the relative rib area of the reinforcing bar [12]. On the other hand, when transverse bars are used, the bond strength increases with an increase in the relative rib area. Thus, a factor of $R_r^{a_8}$ was used to consider the effect of relative rib area on the additional bond strength provided by transverse bars.

According to Zuo and Darwin [12], when transverse bars are used, the value of $f_c^{\prime\,0.25}$ significantly underestimates the additional bond strength provided by transverse bars, and the value of $f_c^{\prime\,0.75}$ is appropriate to consider the effect of compressive strength on the additional bond strength. Thus, a factor of $f_c^{\prime\,a_9}$ was used to evaluate the effect of concrete strength on the additional bond strength provided by transverse bars.

4.5. Proposed bar bond strength model

Combining design parameters shown above, an equation for the bond strength was organized as follows:

$$\tau = a_0 f_c^{\prime\,a_1}\left(\frac{l_a}{d_b}\right)^{a_2}\left[\left(a_3\frac{c_{\min}}{d_b}+a_4\right)\left(\frac{c_{\max}}{c_{\min}}\right)^{a_5}+a_6\left(\frac{c_{\min}}{d_b}\right)^{a_7}R_r^{\,a_8}K_{st}f_c^{\prime\,a_9}\right] \tag{22}$$

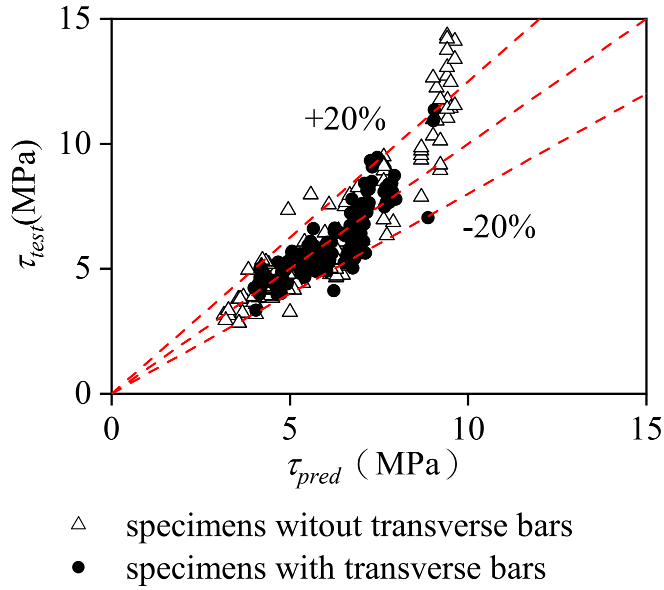

Fig. 4. Comparison of test results and predictions of Eq. (23) in Database 3.

Using the regression analysis of **Eq. (22)** applying Database 1, coefficients a_0 to a_9 were determined. Thus, the proposed bond strength model can be summarized as follows:

$$\tau = 2.55\Psi_d\left(\frac{l_d}{d_b}\right)^{-0.45} f_c^{'\,0.25}(K_c + K_{tr}) = 2.55\Psi_d\left(\frac{l_d}{d_b}\right)^{-0.45} f_c^{'\,0.25}K \tag{23}$$

$$K_c = \left(\frac{c_{\min}}{d_b} + 1\right)\left(\frac{c_{\max}}{c_{\min}}\right)^{0.2} \tag{24}$$

$$K_{tr} = 40.8k_Rk_cK_{sv}f_c^{'\,0.45} \tag{25}$$

Where Ψ_d is the coefficient related to rebar diameter (i.e., Ψ_d= 1.0 for d_b < 25 mm, otherwise, Ψ_d= 0.9); concrete cover ratio is $(c_{\max}/c_{\min})^{0.2} \leqslant 1.60$; k_R is the coefficient of the relative rib area ($=R_r^{0.8}$); k_c is the coefficient of the concrete cover ($=(c_{\min}/d_b)^{-0.8} \leqslant 1.74$); K_{sv} is the coefficient related to the confinement of transverse bars ($= k_nA_{sv,1}/(d_bs)$); k_n is the ratio of n_1 to n_2; s is the spacing of transverse bars ($=l_d / N$); N is the number of transverse bars within l_d; n_1 is the number of legs of a transverse bar on the splitting plane; n_2 is the number of bars developed or spliced along the splitting plane; $A_{sv,1}$ is the cross-sectional area of the transverse bar; and $K \leqslant 5$.

Fig. 2 and Table 4 compare the beam test results of Database 1 with the predictions of the existing methods and the proposed method (**Eq. (23)**). The proposed method predicted the test results better than the existing methods, showing a mean test-to-prediction ratio of 1.00 with Coefficient of Variation(COV) of 0.143.

As shown in Fig. 3(a), for specimens with a development length longer than $50d_b$, the proposed method overestimated the effect of the development length-to-diameter ratio for specimens without transverse bars. According to Seliem et al. [22], sudden failure occurred after the initial splitting crack appeared due to explosive spalling of the cover concrete along the splice length for specimens without transverse bars. When the splice length was relatively long, although splice lengths differed by 30% (i.e., $49d_b$ and $65d_b$), the developed bar stress was almost the same. On the other hand, the use of transverse bars allowed splitting cracks to be developed along with bar splices, thus preventing abrupt spalling failure [28].

As shown in Fig. 3**(b-f)**, the proposed model **Eq. (23)** well reflected the effects of concrete strength, confinement of cover concrete and transverse bars, the maximum concrete cover, rebar diameter, and relative rib area of rebars on bond strength in beam specimens,

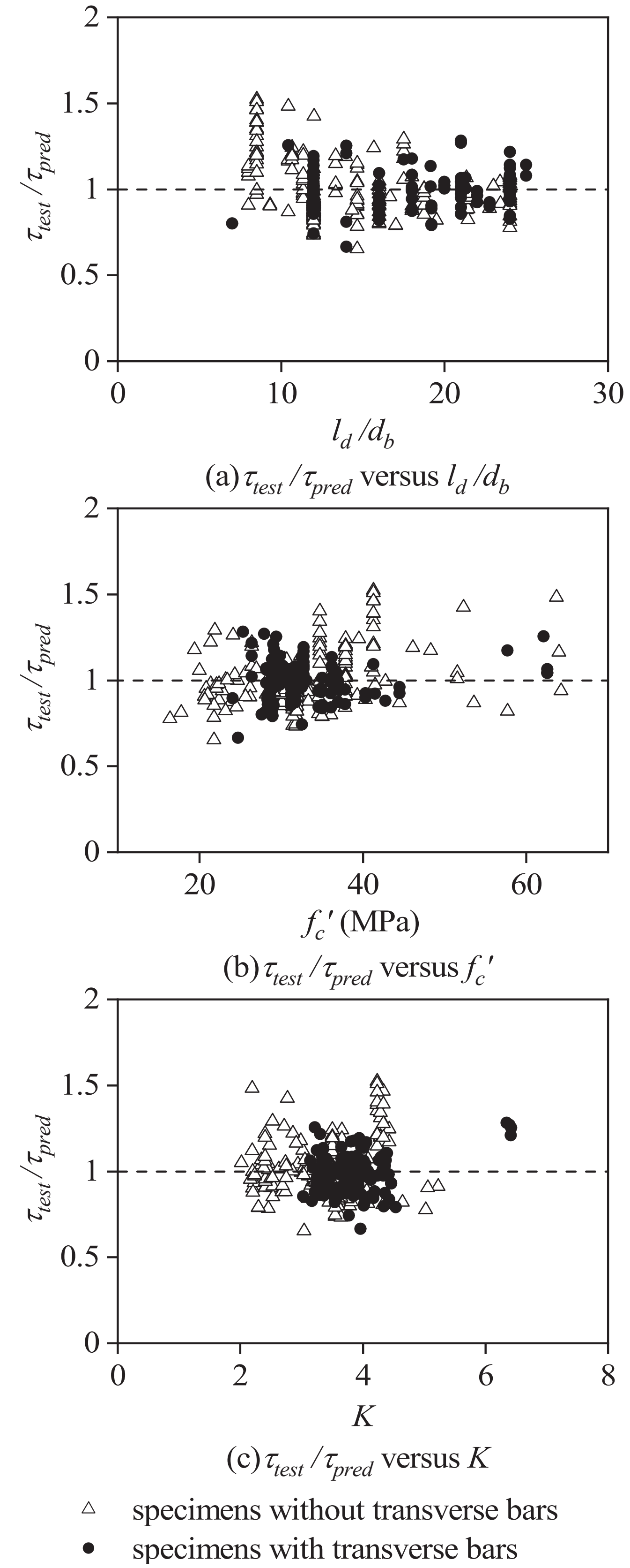

Fig. 5. Variation of test–prediction ratio of Eq. (23) versus test parameters in Database 3.

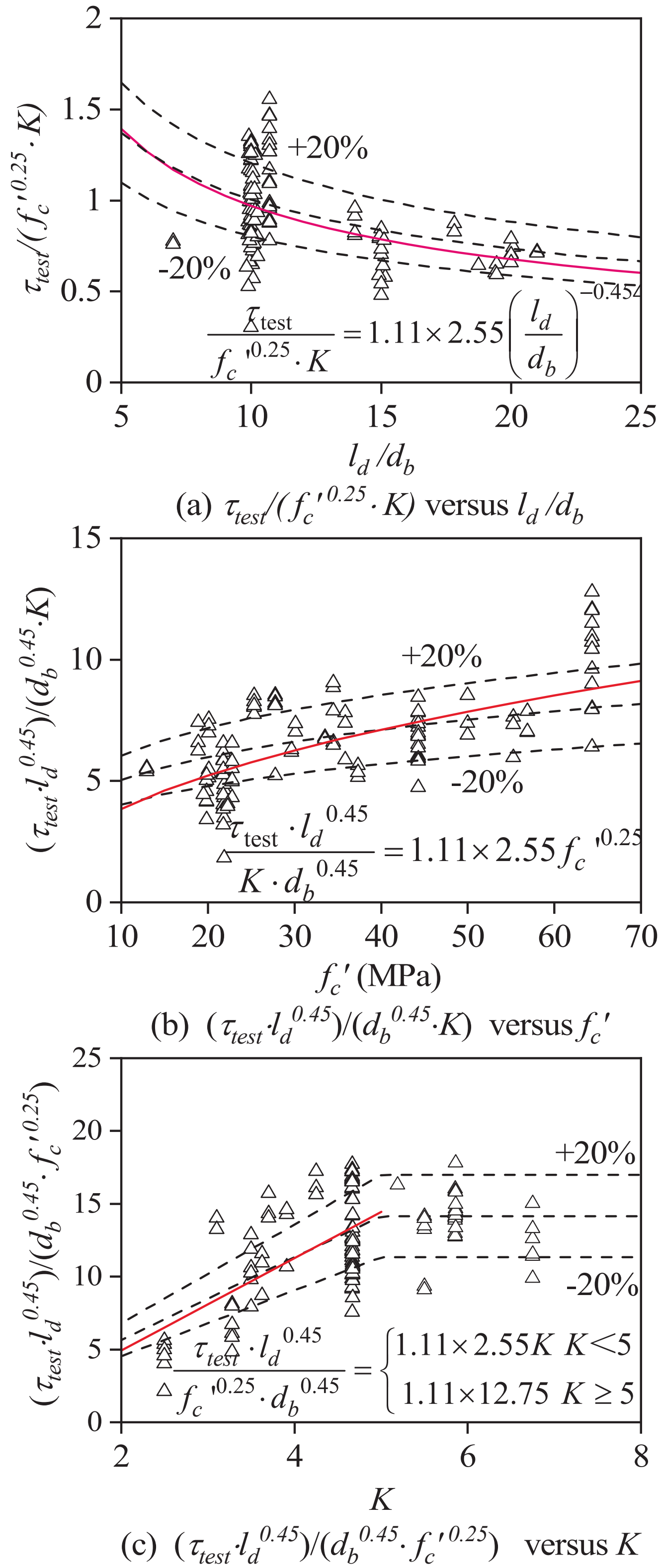

Fig. 6. Normalized bond strength of Database 2 without transverse bars versus test parameters.

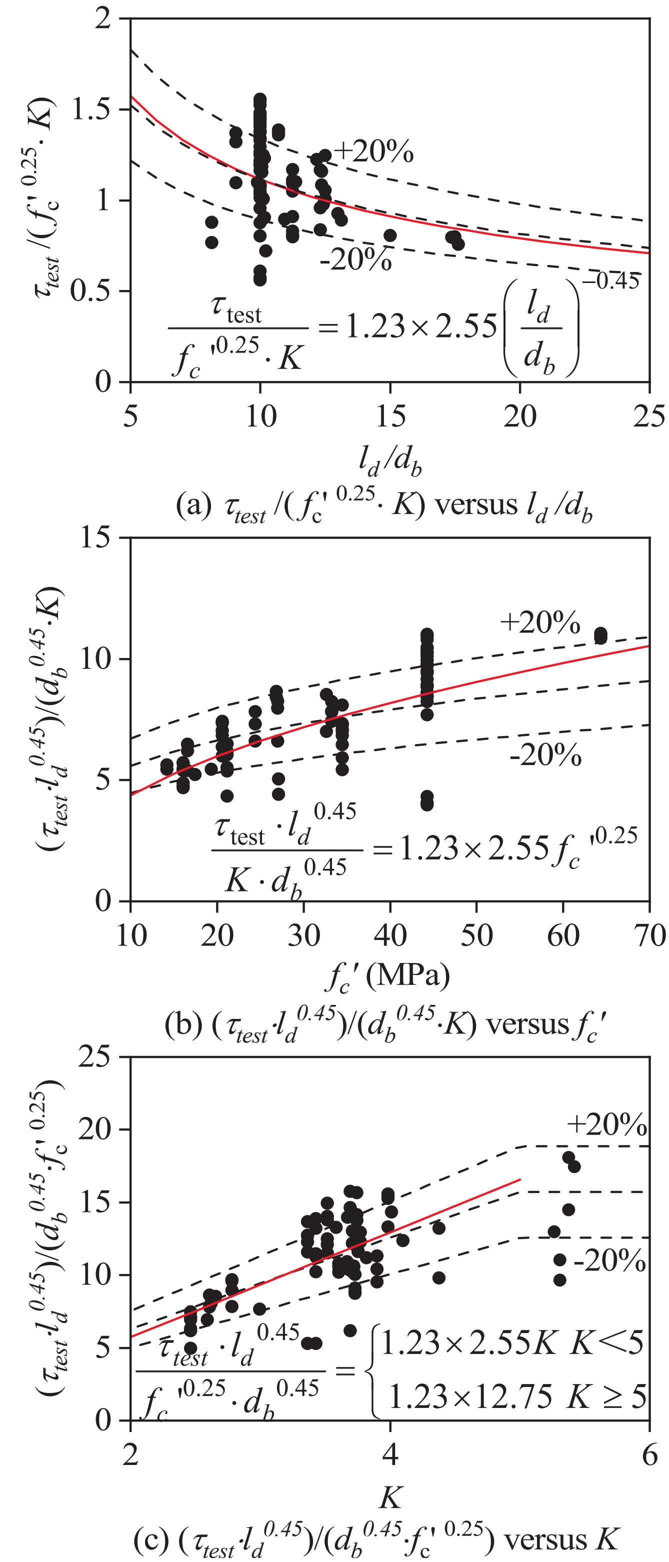

Fig. 7. Normalized bond strength of Database 2 with transverse bars versus test parameters.

respectively.

For direct comparison between the pull-out and beam test results, **Eq.** (23) was applied to the test results of Database 3, and Database 3 excludes beam test specimens with $l_d > 25d_b$ and $f_c' > 65$ MPa. Therefore, test parameter ranges were $7 \leqslant l_d/d_b \leqslant 25$, 10 MPa $\leqslant f_c' \leqslant$ 65 MPa, and $2 \leqslant K \leqslant 6.5$. Table 5 and Figs. 4 and 5 compare the beam test results of Database 3 with the predictions of the proposed method (**Eq.** (23)). The proposed method predicted the test results better than the existing methods, showing a mean value of the test-to-prediction ratio of 1.00 with COV of 0.145.

Table 6
Test–prediction ratio for bond strength models in Database 2.

Pull-out test specimens	Background of GB (Eq.11)		Proposed Model (Eq.23)		Proposed Model (Eq.26)	
	Mean	COV	Mean	COV	Mean	COV
All	1.14	0.254	1.16	0.221	1.00	0.199
without stirrups	1.06	0.283	1.11	0.235	1.00	0.221
with stirrups	1.25	0.192	1.23	0.193	1.00	0.166

5. Analysis of pull-out test database

Due to the significant influence of transverse bars on the pull-out test results, test specimens in Database 2 were separated into two groups for statistical analysis (i.e., specimens with and without transverse bars). Figs. 6 and 7 present the regression analysis results of the normalized bond strength in accordance with each test parameter for pull-out test specimens without and with transverse bars in Database 2, respectively. In these figures, the solid red line indicates the best-fit curve of the normalized bond strength in accordance with each test parameter. The dashed black line indicates the calculation results of **Eq. (23)** multiplied by the mean value of the test-prediction ratio (Table 6).

The development length-to-diameter ratio $(l_d/d_b)^{-0.45}$ well described the degree of uneven distribution of bond stress along the development length (Fig. 6**(a) and 7(a)**). In Fig. 6**(b) and 7(b)**, $f_c^{\prime\,0.25}$ underestimated the effect of concrete strength on the bond strength in the pull-out test. This result indicates that the contribution of concrete strength to bond strength is affected by bond test methods. The restraint factor K addressed well the effects of concrete cover and transverse bars on the bond strength in the pull-out test (Fig. 6**(c) and 7(c)**).

Fig. 8 compares the normalized bond strength with the test results of Databases 2 and 3 according to concrete strength. The bond strength in pull-out test specimens without transverse bars increased slightly compared to beam test specimens without transverse bars. However, when transverse bars were used, the bond strength in the pull-out test specimens was significantly increased.

6. Modeling of concrete contribution and bond strength

6.1. Effect of transverse bars on concrete contribution

Analysis results of the present study showed that the transverse bars increased the effect of concrete strength on bond strength. The bond strength in the specimens without transverse bars is proportional to $f_c^{\prime\,0.25}$. The additional bond strength provided by transverse reinforcement is proportional to $f_c^{\prime\,0.7}$ (refer to **Eq. (23)**). Zuo and Darwin [12] also reported that the bond strength provided by cover and transverse bars are proportional to $f_c^{\prime\,0.25}$ and $f_c^{\prime\,0.75}$, respectively. The reason is that specimens without transverse bars are governed by the splitting failure, which is controlled by the tensile strength of concrete. In this case, the bond strength increases slowly with the increase of concrete compressive strength. On the other hand, the development of splitting cracks is restrained by the transverse bars for specimens with transverse bars. Therefore, concrete in front of rebar ribs is finally crushed with the shear damage of concrete between ribs, resulting in the fully developed compressive strength of concrete.

6.2. Effect of test methods on concrete contribution

Analysis results of the present study showed that the bond strength of the pull-out test specimens is higher than that of the beam test specimens under the same conditions. The results of existing experimental studies [9,44] also reported that the contribution of concrete strength to the bond strength in the beam or double-sided pull-out test (Fig. 9) is less than that in the pull-out test. These results indicate that the stress field of the concrete surrounding the reinforcing bar is affected by the bond test method, which influences the contribution of the concrete strength to the bond performance of the reinforcement. The difference in the stress state of concrete also resulted in significant differences in the crack pattern and bond stress distribution between the beam and pull-out specimens.

In the pull-out test, the stress state of concrete surrounding a reinforcing bar is shown in Fig. 10**(a)**. The ring compressive stress and shear stress caused by the mechanical anchorage of the ribs against the concrete surface are defined as $\sigma_{r,cube}$ and τ_{cube}, respectively. $\sigma_{\theta,cube}$ is the circumferential tensile stress caused by the extrusion pressure of the reinforcing bar ($\sigma_{r,cube}$). The compressive stress caused by the pressure at the end of the cube is defined as $\sigma_{a,cube}$. For the compressive stress $\sigma_{a,cube}$, only splitting cracks appear in the specimens. The bond stress distribution along the reinforcing bar is continuous, and the bond stress direction is consistent.

In the beam test, the stress state of concrete surrounding a rein-

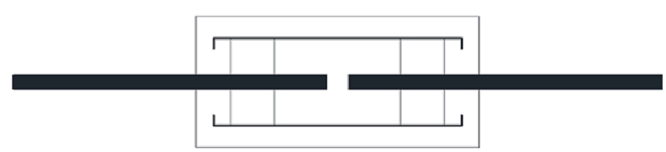

Fig. 9. Double-sided pull-out test specimen.

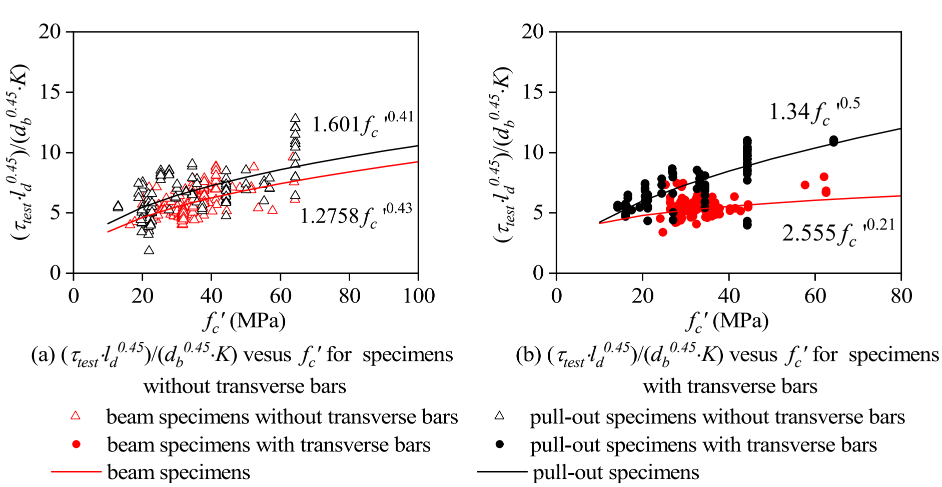

Fig. 8. Normalize bond strength of Databases 2 and 3 versus concrete strength.

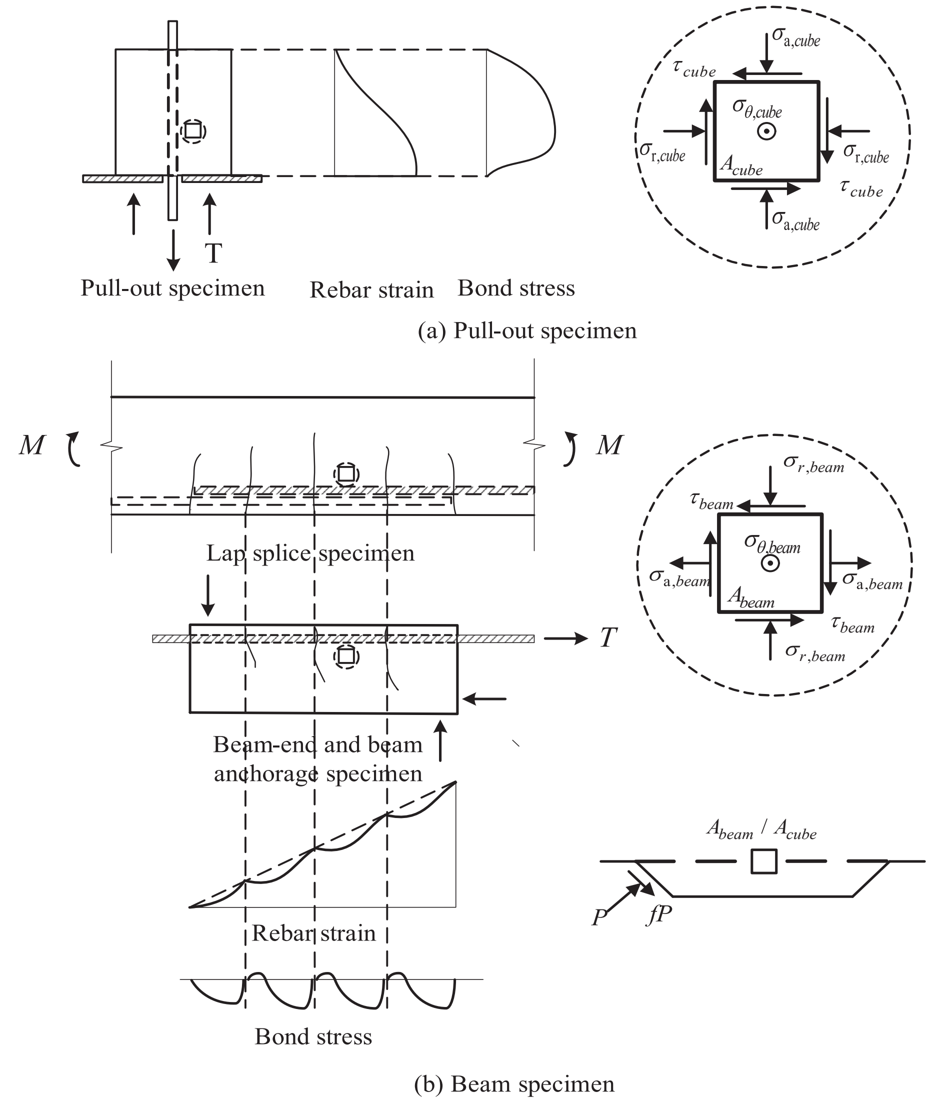

Fig. 10. The stress field of concrete, crack pattern, and bond stress distribution in specimens.

forcing bar is shown in Fig. 10**(b)**. The ring compressive stress and shear stress caused by the mechanical anchorage of the ribs against the concrete surface are defined as $\sigma_{r,beam}$ and τ_{beam} , respectively. $\sigma_{\theta,beam}$ represents the circumferential tensile stress due to the extrusion force of spliced bars on the concrete. $\sigma_{a,beam}$ is the tensile stress caused by the flexure of the beam specimen. Flexural cracks appear in the specimen under tensile stress $\sigma_{a,beam}$. The concrete fails to resist tensile stresses at flexural cracks. Stress redistribution of the reinforcement occurs near the flexure crack. In the zone between the flexural cracks, the reinforcement stress decreases and then increases. Hence, the bond stress changes the direction in this region [16]. As the load increases, the number of flexural cracks increases, and the crack spacing decreases. When the distance between adjacent cracks has become small enough, the bond stress cannot induce enough stress in concrete to cause splitting failure or pullout failure. It can be inferred that if the same local bond strength is assumed and the same development length is applied, the average bond strength in the beam specimen test is lower than that in the pull-out test.

For specimens without transverse bars, splitting failure occurs when the tensile stress (σ_θ) reaches the concrete tensile strength. The splitting tensile strength f_{ts} is positively correlated with the concrete compressive strength f_c', and the power function is used to represent their relationship, whose power is between 0.5 and 0.7 [46–50]. The conversion relation between axial tensile strength f_{sp} and splitting tensile strength f_{ts} is $f_{sp} = 0.9956 f_{ts}^{0.82}$ [51]. Thus, the power exponent of the conversion function between f_{sp} and f_c' is between 0.41 and 0.58. The power exponents of f_c' for the fitted bond strength curves of the beam and pull-out specimens are 0.43 and 0.41, respectively (Fig. 8(a)), which are within the power exponent range of the axial tensile strength.

For specimens with transverse bars, splitting cracks occur when the tensile stress (σ_θ) reaches the concrete tensile strength. After cracking, the circumferential tensile stress of concrete near the splitting cracks decreases significantly and can be ignored, i.e., $\sigma_\theta = 0$ [41], while the additional tensile stress is resisted by transverse bars. With further increased applied load, the splitting-pullout or pullout failure of specimens with transverse bars is controlled by the shear damage of concrete between rebar ribs. When the concrete is in a combined tensile-shear stress state, the shear strength decreases with the increase of normal tensile stress. When the concrete is in a combined compressive-shear stress state, and the ratio of normal compressive stress to compressive strength is less than 0.6, the shear strength increases with the increase of normal compressive stress [52]. In the existing formulas for shear capacity of beams and punching shear capacity of slabs [2–5,53], the power exponent range of concrete strength is about 0.25 to 0.55. For the beam specimens with transverse bars, the concrete between rebar ribs is in a combined tensile-shear stress state, resulting in a low shear strength

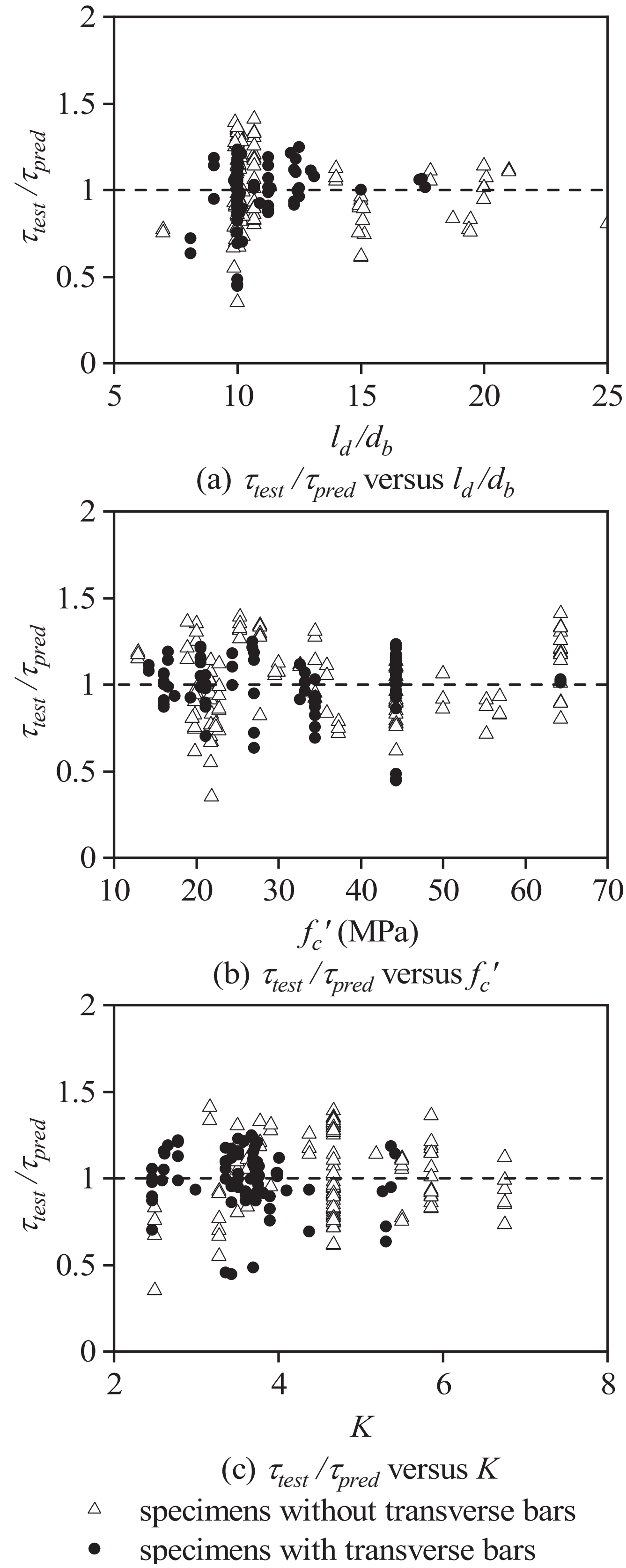

Fig. 11. Variation of test–prediction ratio of **Eq. (26)** versus test parameters in Database 2.

of concrete (Fig. 10**(a)**). The power exponent of 0.21 obtained in this study (Fig. 8(b)) is close to the lower limit of the power exponent in the case of punching shear of slabs. On the other hand, for the pull-out specimens with transverse bars, the concrete between the rebar ribs is in a combined compressive-shear stress state (Fig. 10**(b)**). Therefore, the power exponent of concrete strength of pull-out specimens is about 0.5, which is higher than that of beam specimens (Fig. 8(b)).

6.3. Unified bond strength model

The above analysis indicates that the effect of test methods on the average bond strength can be considered by modifying the function of concrete strength $f(f_c')$. **Eq.** (23) was modified to a unified bond strength equation as follows:

$$\tau = \Psi_d \left(\frac{l_a}{d}\right)^{-0.45} K \cdot f(f_c') \tag{26}$$

$$f(f_c') = \begin{cases} 2.55 f_c'^{\,0.25} & \text{for beam specimens} \\ 1.68 f_c'^{\,0.4} & \text{for pull - out test specimens without trasnverse bars} \\ 1.34 f_c'^{\,0.5} & \text{for pull - out test specimens with trasnverse bars} \end{cases} \tag{27}$$

$$K = K_c + K_{tr} \leqslant 5 \tag{28}$$

Table 6 compares the pull-out test results with the predictions by **Eq. (11)** based on pull-out test results and the proposed models (**Eqs. (23)** and **(26)**). The proposed **Eq. (26)** well predicted the test results, showing a mean value of the test-to-prediction ratio of 1.00 with a COV of 0.199. Fig. 11 shows that **Eq. (26)** appropriately considers the effect of test parameters on the bond strength in pull-out test specimens.

To further verify the validity of the proposed unified model (**Eq. (26)**), based on the database filtering conditions, we selected the existing lap splice [54] and beam-end tests [55] conducted by our research group at Hunan University and 21 pull-out specimens tested by the authors. These specimens have covered the primary bond test methods (lap splice, beam-end, and pull-out tests), and their test parameters (concrete strength f_c', the development length-to-diameter l_a/d_b, and restraint factor K) are similar. The additional bond test results are shown in Table 7.

Fig. 12 shows that the form of the beam specimens (lap splice and beam-end tests) has no significant effect on the bond strength. Furthermore, the proposed unified model based on database analysis can accurately predict the bond strength of pull-out and beam specimens.

The contributions of the development length-to-diameter ratio and restraint factor are consistent across test methods in **Eq. (26)**. However, the stress state of concrete varies depending on the test method, resulting in different contributions of concrete strength. For beam test specimens, the function of concrete contribution is $f_c'^{0.25}$, and for pull-out test specimens, it is approximately $f_c'^{0.5}$. However, each current code only takes into account one type of concrete contribution. ACI 408R-03 [1] and Model Code 2010 [4] use $f_c'^{0.25}$, $f_c'^{0.5}$ is used in ACI 318–19 [2], f_t ($f_c'^{0.55}$) is used in GB 50010–2010 [5], and f_{ctd} ($f_c'^{2/3}$) is used in Eurocode 2. Given the similar stress states of concrete surrounding the reinforcing bar in beam specimens and actual structures, ACI 318–19, Eurocode 2, and GB 50010–2010 all overestimated the effect of concrete strength on bond strength in actual structures. The safety factors of those code equations, on the other hand, have been proven to meet the reliability requirements of each design code.

The development length equations in ACI 318–19 and Eurocode 2 are based on beam test results, and the development length equation (**Eq.** (2)) for GB 50010–2010 is based on the pull-out test results. The prediction accuracy of GB50010-2010 is comparable to that of ACI 318–19 and Eurocode 2 for beam specimens. Thus, combined with the comparative analysis between the beam and pull-out test results, the

Table 7
Summary of additional specimens.

Specimen number	$f_c^{'}$ (MPa)	l_d/d_b	$\frac{c_{\min}}{d_b}$	$\frac{c_{\max}}{c_{\min}}$	K_{sv}	K	b (mm)	h (mm)	τ_{test} (MPa)	$\frac{\tau_{test}}{\tau_{pred}}$ **Eq. (26)**	Test types
L17-1 [54]	29.9	16.9	1.25	6.56	0.49	3.77	300	400	7.16	1.14	lap splice
L17-2 [54]	29.9	16.9	1.25	6.56	0.49	3.77	300	400	6.47	1.03	lap splice
L17-3 [54]	27.6	16.9	1.25	6.56	0.48	3.75	300	400	4.94	0.80	lap splice
30–20-20-5a [55]	27.7	20.0	1.00	1.00	0.73	2.73	300	300	4.69	1.13	beam-end
30–20-20–5 [55]	26.3	20.0	1.00	1.00	1.19	3.19	300	300	5.35	1.12	beam-end
30–20-20-5ab [55]	27.7	20.0	1.5	1.00	0.53	3.03	300	300	5.18	1.13	beam-end
A-1–1	30.6	15.0	2.25	1.00	–	3.25	110	110	7.19	1.13	Pull-out
A-1–2	30.6	15.0	2.25	1.00	–	3.25	110	110	7.65	1.21	Pull-out
A-1–3	30.6	15.0	2.25	1.00	–	3.25	110	110	6.85	1.08	Pull-out
A-2–1	24.0	15.0	2.25	3.11	–	4.08	300	110	6.32	0.88	Pull-out
A-2–2	24.0	15.0	2.25	3.11	–	4.08	300	110	7.76	1.07	Pull-out
A-3–1	24.0	15.0	2.25	3.11	–	4.08	300	200	8.33	1.15	Pull-out
A-3–2	24.0	15.0	2.25	3.11	–	4.08	300	200	6.34	0.88	Pull-out
A-3–3	24.0	15.0	2.25	3.11	–	4.08	300	200	7.63	1.06	Pull-out
A-4–1	30.6	15.0	2.25	2.00	–	3.73	200	200	8.00	1.10	Pull-out
A-4–2	30.6	15.0	2.25	2.00	–	3.73	200	200	8.21	1.13	Pull-out
A-4–3	30.6	15.0	2.25	2.00	–	3.73	200	200	7.73	1.06	Pull-out
A-5–1	30.6	15.0	2.25	2.00	–	3.73	200	110	7.72	1.06	Pull-out
A-5–2	30.6	15.0	2.25	2.00	–	3.73	200	110	7.99	1.10	Pull-out
A-5–3	30.6	15.0	2.25	2.00	–	3.73	200	110	7.79	1.07	Pull-out
B-1–1	24.0	15.0	2.00	1.00	0.31	3.31	100	100	6.11	0.95	Pull-out
B-1–2	24.0	15.0	2.00	1.00	0.31	3.31	100	100	6.28	0.98	Pull-out
B-1–3	24.0	15.0	2.00	1.00	0.31	3.31	100	100	6.15	0.96	Pull-out
B-2–1	24.0	15.0	2.00	1.00	0.56	3.56	100	100	6.93	1.00	Pull-out
B-2–2	24.0	15.0	2.00	1.00	0.56	3.56	100	100	7.08	1.03	Pull-out

Note: The diameter of L17 is 16 mm, whereas the diameter of other specimens is 20 mm; the relative rib area is 0.087; no measurement data are available for A-2–3, and post-yield damage occurs for B-2–3.

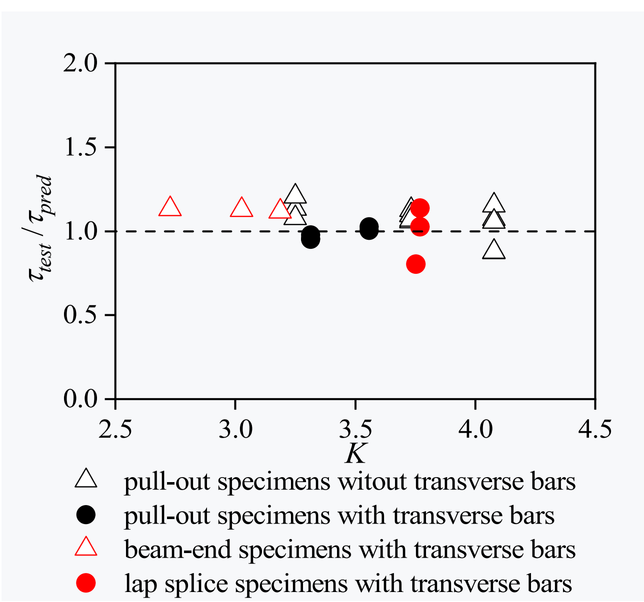

Fig. 12. Variation of test–prediction ratio of **Eq. (26)** versus K for the additional specimens.

pull-out test method is still effective in evaluating the development length and bond strength for the concrete strength range of GB 50010–2010.

7. Summary and conclusions

The effect of test methods on bond strength was investigated in this study. Existing test results were established for beam test specimens (Database 1) and pull-out test specimens (Database 2). For direct comparison of test results, the beam test data (Database 3) was extracted from Database 1 and had nearly the same test parameter range as Database 2. The effects of test parameters on bond strength were studied, and regression analysis was used to develop a unified bond strength model that addressed bond test methods. The primary findings are summarized below:

1. A bond strength model was proposed based on existing beam specimens (Database 1)and bond mechanisms. In addition, a new factor k_c was proposed to reflect the effect of the concrete cover on the additional bond strength provided by transverse bars. The proposed model can better meet the test phenomenon and predict the bond strength more accurately than current design codes.
2. A comparative analysis was performed between beam test results (Database 3) and pull-out test results (Database 2). Results showed that both beam and pull-out test specimens were affected by the same coefficients related to the development length-to-diameter ratio and restraint conditions, except for the degree of concrete strength.
3. The stress state of concrete varies depending on the test method, resulting in different contributions of concrete strength. The contribution of concrete strength to bond strength was greater in pull-out test specimens than in beam test specimens. Transverse bars can improve the contribution of concrete strength to bond strength.
4. Based on the bond strength model of beam specimens, a unified bond strength equation was proposed using a concrete strength conversion factor. The unified model applies to both beam and pull-out test specimens with a development length of $l_d/d_b \geqslant 7$. The additional specimens(lap splice, beam-end, and pull-out tests) verified the prediction accuracy of the proposed unified model.
5. The development length in GB 50010–2010 was prescribed based on pull-out test results, while the development length equations were empirically developed by beam specimens for the other design codes. However, the prediction accuracy of GB50010-2010 is comparable to that of ACI 318–19 and Eurocode 2 for beam specimens. Thus, combined with the comparative analysis between the beam and pull-out test results, the pull-out test method is still effective in evaluating the development length and bond strength in the concrete strength range of GB 50010–2010.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 51878260).

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