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Experimental investigation on bond behaviours of deformed steel bars embedded in early age concrete under biaxial lateral pressures at low curing temperatures

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Abstract

The unexpected temperature drop during the concrete curing process could degrade the concrete properties at early age, and then decrease the bond behaviour between concrete and reinforcing steel bars. To assess the effect of low curing temperature on structural safety, it is significantly important to investigate the bond behaviour of early age concrete under such extreme environmental conditions. In this study, pull-out tests were conducted on the early-age concrete specimens with embedded deformed steel bars at the low curing temperature of 0°C and the normal temperature of 20°C. All specimens were subjected to biaxial lateral pressures varying from 0.1$f_{cu}$ to 0.4$f_{cu}$ to investigate the effect of simultaneous confining pressure. The results indicated that comparing with the specimens cured at 20°C, the bond strength for the specimens cured at 0°C decreased significantly at earlier ages of 3 and 7 days. However, the bond strength increased steadily with the increase of the curing age. Eventually, the concrete specimens at the 28-day age reached the same bond strength for both low and normal curing temperatures. In addition, the average slip displacements corresponding to the ultimate bond stresses (bond strengths) for the specimens at the low curing temperature was slightly lower than those at the normal curing temperature. Based on the experimental results, an empirical model of bond stress-slip relationship was proposed for the early age concrete at low curing temperatures. Comparing with other existing models, the proposed bond stress-slip relationship agreed well with the experimental results, validating its applicability for the early age concrete at low curing temperatures.

Keywords: Bond behaviour; early age concrete; biaxial lateral pressure; low curing temperature; bond stress-slip relationship
Introduction

Extensive applications of reinforced concrete structures and demands for reducing the duration of construction projects so as to decrease construction expenditures show the importance of knowing concrete properties at early ages especially the bond behaviours of reinforced concrete. A significant drop of environmental temperatures during either casting or curing of concrete could cause dramatic reduction of its structural performance. A collapse accident of a cooling tower under-construction has been reported [1], where the bond failure between the early age concrete and reinforcing steel bars occurred due to a sharp temperature drop during construction. Meanwhile, considering that beam-column joints usually are subjected to lateral pressure during service [2], the combined effects of stress states and casting/curing temperatures on the material properties and structural performances of early age concrete can be more complex. Therefore, to precisely assess structural safety affected by extreme temperature conditions, it is of significant importance to investigate the bonding behaviour of early age reinforced concrete by coupling stress and temperature conditions.

At early age, the concrete compressive strength in reinforced concrete structures is undoubtedly less than that of mature concrete because the cement hydration process is not completed, which significantly influences the bond strength between the reinforcing steel bars and surrounding concrete. Shah et al. [3] conducted pull-out tests to study the influence of curing age on the bond characteristics and found that the bond strength for plain steel bars with concrete was not affect by the age, while the bond strength of deformed steel bars increased with the increasing concrete age. They also found that the progress from early age concrete to mature concrete caused the bond failure mode to change from brittle shear failure to flexural ductile failure. Chapman and Shah [4] conducted the pull-out tests on deformed bars to explore the influence of concrete age, where the increase of bond strength with concrete age was confirmed. Hughes and Videla [5] investigated the effects of concrete age and other parameters, including bar diameter, concrete cover thickness, transverse reinforcement and anchorage length, on the bond behaviour to provide design criteria for early age concrete. They also found that the average bond strength increased with age at a greater rate than compressive and tensile strengths
of concrete. Cooper [6] found that despite the effect of early age loading on concrete deflection and
crack propagation, it had no influence on the ultimate bond stress (bond strength). Song et al. [7]
conducted pull-out tests to assess the effects of early age and ratio of concrete cover to bar diameter
on bond strength and found that the bond strength got enhanced with the increasing compressive
strength. Shen et al. [8] conducted pull-out tests to study the bonding behaviour between high-strength
concrete and steel bars and found that the bond strength was enhanced as the concrete strength
increased. However, Fu and Chung [9] found that the bond strength between cement paste and
stainless steel fibres decreased with the increasing concrete age from 1 to 28 days, especially from 1
to 14 days, due to the increased interfacial voids. Aiming at the influence of low curing temperature
on the properties of early age concrete, Banthia and Trottier [10] conducted pull-out tests on hooked
fibres embedded in concrete at five curing temperatures of -5°C, -15°C, 2°C, 22°C and 38°C, together
with the curing ages of 1, 3, 7, 14, 28 and 90 days. They found that the pull-out loads of hooked fibres
depended on the curing temperature and lower bond strengths were obtained under lower curing
temperatures. In addition, early freezing had a negative effect on the ultimate pull-out loads although
the pull-out energies remained fairly the same.

Due to the complex stress distributions around concrete beam-column joints, investigations on the
effect of lateral stress on the bond behaviour between concrete and reinforcing steel bars were
performed, and various combinations of lateral loads were considered to apply. Robin and Standish [2,
11] conducted pull-out tests and semi-beam bond tests on plain and deformed steel bars embedded in
concrete and found that the lateral pressure had a significant positive influence on the average bond
strength of the steel bars. With the magnitudes of the lateral stresses close to the concrete strength, the
bond capacities increased by 200% and 75% for plain and deformed steel bars with the same size,
respectively. The lateral stresses not only increased the ultimate bond stress (bond strength) but also
enhanced the bond stress level corresponding to the same bond slip. Xu et al. [12] conducted pull-out
tests on 91 specimens to explore the effect of lateral pressures on the bond behaviour of plain and
deformed steel bars. For the specimens with plain bars, when the lateral pressure increased from 0 to
0.6f_{cu}, the bond capacity was enhanced by 300%. For the specimens with embedded deformed bars,
when lateral pressure was applied, the specimens sustained pull-out failure. By contrast, where there
was no lateral pressure, the specimens sustained splitting failure. Li et al. [13,14] studied the effect of
loading rate on the bond behaviour of plain and deformed bars embedded in concrete, and found that
under lateral pressure, the bond strength increased with the loading rate. Wu et al. [15] investigated
the bonding behaviour of lightweight concrete subjected to uniaxial and biaxial lateral pressures, and
found that the bond strength increased monotonically with the increase of lateral pressures.

In addition, bond stress-slip models were proposed based on the experimental results of bond
stress-slip relationships. The predicting equations were derived by using the regression analysis on the
experimental results. The influencing parameters including concrete compressive strength, steel bar
diameter, concrete cover, bar rib configurations, anchorage length, and lateral pressure have been
extensively studied [16–19]. Although previous studies investigated the bond behaviour of concrete
under different conditions, lack of experimental investigations on the influence of low curing
temperatures on bond behaviour is obvious.

The aim of this study is to investigate the bond behaviours of deformed bars embedded in the early
age concrete under biaxial lateral pressures at low curing temperatures. Pull-out tests were conducted
on a total of 150 cubic specimens at low and normal curing temperatures of 0ºC and 20ºC,
respectively. The bond properties of concrete at the curing ages of 1, 3, 7, 14 and 28 days were
investigated. In addition, the biaxial confining pressures, varying from 0.1$f_{cu}$ to 0.4$f_{cu}$, were applied
simultaneously. This study explored the ultimate bond stresses (bond strengths), the corresponding
bond slips, and the residual bond strengths at low and normal curing temperatures. Eventually, an
empirical equation for bond stress-slip relationship was proposed by conducting the regression
analysis on the test results of the investigated parameters including curing temperature, curing age and
lateral pressure. Finally, the proposed model was compared with other existing empirical models and
experimental data to validate its applicability for early age concrete under the coupling conditions of
low curing temperatures and lateral pressures.
Experimental program

In this experimental investigation, standard commercial deformed steel bars in China with a 22 mm nominal diameter were adopted. The material properties of steel bars are listed in Table 1. Ordinary Portland cement was used to make concrete specimens with a 40 MPa nominal compressive strength. The specified mix proportions and material properties of concrete are listed in Table 2. Cubic wooden moulds with an internal side length of 150 mm were prepared and reinforced bars were placed and fixed well in the centre of the moulds as shown in Fig. 1. The embedded length of the reinforced bar embedded in concrete was defined as 5 times of the nominal bar diameter, i.e. 110 mm, according to the previous studies [14,20,21]. In order to prevent additional restraints, the unbonded lengths near the top and bottom of the concrete specimens were encased with two 20 mm long PVC tubes to isolate these steel parts from direct contacts with the surrounding concrete. To avoid cement paste penetration, the gaps between the steel bar and PVC tubes were filled with plastic tapes. The direction of the reinforcing bar ribs was adjusted as shown in Fig. 1 and the steel bars were fixed well with silica glue to prevent any movement during casting.

Table 1

<table>
<thead>
<tr>
<th>Material properties of the embedded reinforcing steel bars.</th>
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<tr>
<td>Nominal diameter $D$ (mm)</td>
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<td>Yield strength $f_y$ (MPa)</td>
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<td>Elastic modulus $E_s$ (GPa)</td>
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Table 2

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<th>Mix proportions and material properties of the concrete.</th>
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<td>Concrete grade</td>
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<td>Target compressive strength $f_{cu}$ (MPa)</td>
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<tr>
<td>Cement : water : sand : coarse aggregate</td>
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<tr>
<td>Elastic modulus $E_c$ (GPa)</td>
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</table>
In total, 50 groups of specimens were prepared for the pull-out tests with 3 duplicate specimens in each group. Two large different groups with the curing temperatures of 0°C and 20°C were categorised as the low and normal curing temperature groups respectively to investigate the effects of curing temperatures on the bond behaviour of deformed steel bars embedded in concrete. Five lateral load combinations, varying from 0.1$f_{cu}$ to 0.4$f_{cu}$, were designated to reflect different stress states in the surrounding concrete. These lateral load combinations for two different curing temperatures are listed in Tables 3 and 4, respectively. The lateral pressures $\sigma_1$ and $\sigma_2$ on the concrete surfaces were perpendicular and parallel to the ribs of the deformed bars as shown in Fig. 1(b). In addition, five curing ages of 1, 3, 7, 14 and 28 days were adopted to evaluate the influences of concrete curing ages. After casting, the specimens were immediately put in the curing room with the specified curing temperatures of 20°C and 0°C and the relative humidity of 95% to realise the normal and low temperature conditions, respectively. In addition, for each curing age and curing temperature group, three 150 mm standard cubic specimens were made to measure the concrete compressive strength.
Table 3

Experimental loading and environmental conditions and test results for 20°C curing temperature.

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<th>Temperature (°C)</th>
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Table 4

Experimental loading and environmental conditions and test results for 0°C curing temperature.

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<td>11.98</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>14</td>
<td>0</td>
<td>0.49</td>
<td>0.62</td>
<td>-0.70</td>
<td>3.04</td>
<td>17.68</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>28</td>
<td>0</td>
<td>0.52</td>
<td>0.64</td>
<td>-2.75</td>
<td>4.77</td>
<td>19.17</td>
</tr>
</tbody>
</table>

Pull-out tests were conducted in a hydraulic servo-controlled tri-axial testing machine, as shown in Fig. 2. Two horizontal actuators and one vertical actuator were exerted to apply lateral compressive loads and pull-out load, respectively. Spherical, self-aligning heads were equipped at the ends of the horizontal arms and the bearing platens were fixed on the spherical heads to exert a uniform lateral pressure on the sides of the specimens. The set-up of the loading on the specimen in the testing machine is illustrated in Fig. 3.
Due to the sensitivities of concrete to the testing temperature and age, each specimen was tested immediately after being taken out of the curing room. Firstly, each side surface of the specimen was covered by two layers of thin PVC films smeared with grease to reduce the effect of friction on the results. The specimen was adjusted in the centre of the machine and the top side of the steel bar was fixed to the vertical actuator of the machine with a 300 kN load capacity. Thereafter, two pairs of linear voltage displacement transducers (LVDTs) were installed at the top and bottom sides of the specimen as shown in Fig. 3. The required lateral pressures were then applied through the horizontal actuators onto the specimen. Eventually, the pull-out force was gradually applied through the vertical
actuator at a displacement rate of 0.02 mm/s. During the testing, all measurable parameters including
the pull-out load, the relative displacements between the steel bar and surrounding concrete termed as
bond slips at both loaded and free ends of the steel bar were monitored and recorded by using a data
acquisition system. The bond slip was then obtained by averaging the bond slips at both loaded and
free ends of the steel bar. Besides, the bond stress was assumed to be uniformly distributed along the
bonded length of the steel bar embedded in the concrete [22], and was calculated by dividing the pull-
out load by the bonded area between the steel bar and concrete as:

\[ \tau = \frac{P}{\pi d l_b} \]  

(1)

where \( \tau \) is the average bond stress, \( P \) is the pull-out load, \( d \) is the nominal diameter of the steel bar,
and \( l_b \) is the bonded or embedment length of the steel bar in the concrete.

Results and discussion

In this experimental investigation, 50 groups of specimens were tested under five combinations of
lateral pressures, two different curing temperatures and five curing ages. Tables 3 and 4 also include
the experimental conditions and the mean values of the test results with respect to 20ºC and 0ºC
curing temperatures, respectively. In these tables, \( \sigma_1/f_{cu} \) and \( \sigma_2/f_{cu} \) represent the relative confining
pressures parallel and perpendicular to the ribs of the deformed steel bars. Besides, the ultimate bond
stress (bond strength), the corresponding slip, and the ratio of the residual bond strength to the
ultimate bond stress (bond strength) are denoted by \( \tau_u, s_0 \) and \( k_r \), respectively. The curve shape
parameters are denoted by \( \alpha \) and \( \beta \) for the ascending and descending branches of the bond stress-slip
curves, respectively. It should be noted that due to the very low concrete strength at the 1-day age
under the low curing temperature of 0ºC, the unequal lateral pressures could not be applied on the
sides of the specimens except for \( \sigma_1/f_{cu} = \sigma_2/f_{cu} = 0.4 \). Therefore, almost no test results for this testing
condition included in Table 4.

Failure modes

The specimens which were subjected to higher lateral pressures sustained pull-out failure modes,
where the bond strength along the steel bar ribs with the surrounding concrete was exceeded and the steel rebars were pulled out of the concrete. Thus, a complete bond stress-slip curve has three distinctive branches including ascending, descending and residual portions. Figs. 4(a) to (c) illustrate the specimens sustaining pull-out failure where lateral pressures prevented cracks to propagate into the concrete cover. However, when the bursting stress in the concrete cover exceeded its tensile strength or cracking resistance, the bar ribs would split the concrete cover and splitting failure would happen. For this type of failure, only the ascending branch of the complete bond stress-slip curve could be observed. Nevertheless, in the current experimental study, splitting failure did not occur. The specimens which were subjected to lower lateral pressures sustained the mixed splitting and pull-out failure. As shown in Figs. 4(d) to (f), although the splitting cracks were visible on the concrete cover, the steel bars were pulled out of the concrete at the same time and the bond stress-slip curve contained three distinctive branches. The same phenomenon was also observed in some previous study [2].

(a) Pull-out failure ($\sigma_1/f_{cu} = 0.1$, $\sigma_2/f_{cu} = 0.1$; Age = 3 days; $0^\circ$C)

(b) Pull-out failure ($\sigma_1/f_{cu} = 0.2$, $\sigma_2/f_{cu} = 0.1$; Age = 3 days; $0^\circ$C)
(c) Pull-out failure ($\sigma_1/f_{cu} = 0.4, \sigma_2/f_{cu} = 0.4; \text{Age} = 7 \text{ days; } 0\degree\text{C})$

(d) Mixed splitting and pull-out failure ($\sigma_1/f_{cu} = 0.1, \sigma_2/f_{cu} = 0.1; \text{Age} = 14 \text{ days; } 20\degree\text{C})$

(e) Mixed splitting and pull-out failure ($\sigma_1/f_{cu} = 0.1, \sigma_2/f_{cu} = 0.1; \text{Age} = 14 \text{ days; } 0\degree\text{C})$
(f) Mixed splitting and pull-out failure ($\sigma_1/f_{cu} = 0.1$, $\sigma_2/f_{cu} = 0.1$; Age = 14 days; 0°C)

Fig. 4. Typical test specimens with various failure modes.

4 Ultimate bond stress (bond strength)

Fig. 5 illustrates the relationship between the concrete compressive strength and the curing age of the specimens for the curing temperatures of 0°C and 20°C. It can be seen that at the early curing ages of 1, 3 and 7 days, the differences in the compressive strengths under different curing temperatures were significant due to the low hydration degree of concrete under the low curing temperature. However, the results showed approximately the same compressive strengths at the ages of 14 and 28 days under both low and normal curing temperatures. It could be due to the fact that much higher hydration degrees were realised in the concrete specimens by the age of 14 days for both curing temperatures resulted than those at early curing ages. Similar phenomena were reported in the previous studies [5,6]. Fig. 6 illustrates the comparisons of the ultimate bond stresses (bond strengths) at different curing ages and curing temperatures under the lateral pressures of $\sigma_1 = \sigma_2 = 0.1 f_{cu}$. It can be seen that the low curing temperature had obvious negative effect on the ultimate bond stress (bond strength) at the age of 3 days. However, this negative effect of the low curing temperature on the bond strength became insignificant when the curing age increased to 7, 14 and 28 days. In general, the experimental results showed that the low curing temperature had insignificant influence on the bond strength of the deformed bars embedded in the concrete after the curing age of 14 days for other lateral pressures. Banthia and Trottier [5] reported similar phenomena for steel fibres embedded in concrete for different curing temperatures.
Fig. 5. Relationship between concrete compressive strength and curing age under different curing temperatures.

Fig. 6. Comparisons of ultimate bond stresses (bond strengths) at different curing ages under lateral pressures of \( \sigma_1 = \sigma_2 = 0.1f_{cu} \).

Fig. 7 illustrates the influence of the applied lateral pressures on the ultimate bond stress (bond strength) at the curing temperatures of 20°C and 0°C. At the normal curing temperature, an increase of the bond strength can be seen for higher lateral pressures, due to the fact that the lateral pressures prevented the internal cracks from further propagating in concrete. At the low curing temperature, the applied lateral pressures had little effect on the ultimate bond stress (bond strength) at the curing ages of 3 and 7 days. However, the influence of the applied lateral pressures became significant at the curing ages of 14 and 28 days.
In order to reflect the influences of lateral pressures and concrete curing age on the ultimate bond stress (bond strength), Eqs. (2) and (3) are proposed based on the regression analysis on the test results to predict the ultimate bond stress (bond strength) for 0ºC and 20ºC, respectively:

\[
\tau_u = 5.125 + 0.37t + 0.188\left\{\frac{\sigma_1 + \sigma_2}{\sigma_1 / \sigma_2}\right\}, \quad \text{for 0ºC curing temperature} \tag{2}
\]

\[
\tau_u = 9.837 + 0.255t + 0.183\left\{\frac{\sigma_1 + \sigma_2}{\sigma_1 / \sigma_2}\right\}, \quad \text{for 20ºC curing temperature} \tag{3}
\]

In these equations, the combination of the applied lateral pressures is used as a parameter to reflect the effect of the simultaneous stresses \(\sigma_1\) and \(\sigma_2\). Here, \(t\) represents the curing age of concrete in days.

Fig. 8 illustrates the comparisons of the experimental and predicted values of the ultimate bond stress (bond strength) under the curing temperatures of 0ºC and 20ºC. In these figures, \(\tau_u^{\text{exp}}\) represents the predicted ultimate bond stress (bond strength) values from Eqs. (2) and (3) and \(\tau_u^{\text{exp}}\) represents the experimental ones. The correlation coefficients are equal to 0.79 and 0.65 for the compared results under the curing temperatures of 0ºC and 20ºC, respectively, indicating that the proposed empirical equations are in good agreements with the experimental results.
At 20°C curing temperature

(b) At 0°C curing temperature

Fig. 8. Comparisons of the experimental and regression results of \( \tau_u \) for different curing temperatures

**Bond slip corresponding to the ultimate bond stress (bond strength)**

Fig. 9 shows the relationship between the bond slip corresponding to the ultimate bond stress (bond strength), \( s_0 \), and the curing age of concrete under different lateral pressures for the curing temperatures of 0°C and 20°C. In these figures, the average value of the lateral pressures in two orthogonal directions is denoted by \( \sigma_m \) (\( \sigma_m = \frac{\sigma_1 + \sigma_2}{2} \)). Each group of specimens subjected to different combinations of lateral pressures are presented with different symbols.

Fig. 9. Relationship between bond slip \( s_0 \) and concrete curing age under different lateral pressures for different curing temperatures
Fig. 9 shows an approximately increasing tendency of the bond slip $s_0$ with the increase of concrete curing age under different combinations of lateral pressures. However, it should be noted that the bond slip $s_0$ corresponding to $\sigma_m/f_{cu} = 0.1$ showed a decreasing tendency, particularly at the age of 14 days. Usually, with the increase of the ultimate bond stress (bond strength) $\tau_u$, the larger resistance should be provided to result in larger bond slip. Based on the results of $\tau_u$ versus to curing age shown in Fig. 7(a), the value of $\tau_u$ at the age of 14 days under the lateral pressure combination of $\sigma_1/f_{cu} = \sigma_2/f_{cu} = 0.1$ for 20°C curing temperature was unreasonably low. This also affected the results of $s_0$ shown in Fig. 9(a). Therefore, there may be something wrong during casting of this series of specimens. In addition, the mean values of $s_0$ at the low curing temperature were slightly lower than those at normal curing temperature, varying from 1.44 mm to 4.77 mm for 0°C curing temperature and from 0.97 mm to 4.54 mm for 20°C curing temperature.

Two empirical equations (4) and (5) are proposed to predict the magnitude of $s_0$ for different curing temperatures and lateral pressures. Fig. 10 illustrates the relationships between the predicted and experimental results of $s_0$, where $s_0^{exp}$ and $s_0^{pre}$ represent the experimental and predicted results of $s_0$ respectively. The correlation coefficients corresponding to the curing temperatures 0°C and 20°C are 0.60 and 0.65, respectively.

\[
s_0 = 0.942 + 0.054t + 1.292 \left( \frac{\sigma_1}{f_{cu}} \right) + 2.512 \left( \frac{\sigma_2}{f_{cu}} \right), \quad \text{for 0°C curing temperature} \quad (4)
\]

\[
s_0 = 1.111 + 0.056t + 4.018 \left( \frac{\sigma_1}{f_{cu}} \right) - 0.348 \left( \frac{\sigma_2}{f_{cu}} \right), \quad \text{for 20°C curing temperature} \quad (5)
\]
Fig. 10. Comparisons of the predicted and experimental results of bond slip $s_0$ at the ultimate bond stress (bond strength) for different curing temperatures.

Residual bond strength

After the bond stress reached its ultimate value, it dropped steeply to $\tau_r$, which can be denoted as the residual bond stress or the residual bond strength. Eventually, the bond slip $s_0$ kept increasing without variations of the residual bond stress. Thus, the bond stress can be considered as a residual strength when the bond slip value exceeds 10 mm (see Fig. 11). The ratio of the residual bond strength ($\tau_r$) to the ultimate bond stress (bond strength) ($\tau_u$) is denoted as $k_r$. Fig. 12 illustrates the variations of $k_r$ under different concrete curing ages and lateral pressures for the curing temperatures 0ºC and 20ºC. Each combination of lateral pressures is represented by a different symbol. $k_r$ varied from 0.32 to 0.52 for the specimens cured at 0ºC and from 0.32 to 0.65 for the specimens cured at 20ºC. The test results indicate that the biaxial lateral pressures had no significant effects on the ratio of the residual bond strength to the ultimate bond stress (bond strength).
Fig. 11. Typical complete bond stress-slip curve

Fig. 12. $k_r$ values for different lateral pressures, curing ages and curing temperatures

**Bond stress–slip relationships**

As mentioned above, the complete bond stress-slip relationship illustrated in Fig. 11 consists of three branches, i.e. ascending, descending and residual portions. Some models have been proposed to indicate the bond stress-slip relationship [23]. However, most studies aimed at the mature concrete at normal curing temperature without considering the effects of low curing temperature on early age concrete. Thus, based on the existing models, the following expression of the bond stress-slip relationship is proposed for early age concrete at low curing temperatures:
Based on the regression analysis on the experimental results, a conditional equation has been proposed for the ascending and descending portions of the bond stress versus bond slip curve. The independent parameters are $\tau_u$ and $s_0$ which are determined from the prediction equations (2) to (5). $k_r$ was taken as the constant mean values of 0.46 and 0.42 for the curing temperatures of 20°C and 0°C, respectively. Both portions contain the shape parameters which represent the steepness or flatness of the curve. In Eq. (6), the parameters $\alpha$ and $\beta$ reflect the shapes of the ascending and descending branches of the curves, respectively, which are obtained from the regression analysis on the experimental results. The values of $\alpha$ and $\beta$ are also listed in Tables 3 and 4.

Fig. 13 illustrates the comparisons of the bond stress-slip relationships predicted using Eq. (6) with the experimental results at different curing ages and under different load combinations for the low temperature curing at 0°C. In addition, other two bond stress-slip relationships proposed by Li et al. [14] and Wu et al. [15] are also included in Fig. 13 for comparisons. In this experiment, the loading rate was 0.02 mm/s, and the ratio of the concrete cover to the bar diameter was 2.9. By utilizing these parameters in other two models, the bond stress-slip relationships can be obtained. It can be seen that comparing with other two models [14,15], Eq. (6) exhibits better agreements with the experimental results in this study, especially in the cases of earlier curing age and low curing temperature. The main reason for the wide gaps at earlier age is that the proposed model in this study considered the bond behaviours of the deformed steel bars embedded in concrete under both early curing age and low curing temperature conditions, whereas the two quoted models [14,15] were derived from the test results on the mature concrete at normal curing temperature. Meanwhile, it can be seen that at the age of 28 days, the ultimate bond stresses (bond strengths) predicted from the three models reached the almost same level. Therefore, the effect of low curing temperature on the bond behaviour is more significant for early age concrete, where the magnitudes of the bond strength and the shapes of the bond stress-slip relationship are obviously different. It is necessary to establish the bond stress-slip relationship.
relationship aiming at the early age concrete at low curing temperatures, which would be helpful to
assess the safety of reinforced concrete structures under unpredicted extreme conditions.

(a) At 3-day age; $\sigma_1 = 0.2 f_{cu}$, $\sigma_2 = 0.1 f_{cu}$

(b) At 3-day age; $\sigma_1 = 0.4 f_{cu}$, $\sigma_2 = 0.2 f_{cu}$

(c) At 7-day age; $\sigma_1 = 0.2 f_{cu}$, $\sigma_2 = 0.1 f_{cu}$

(d) At 7-days age; $\sigma_1 = 0.2 f_{cu}$, $\sigma_2 = 0.2 f_{cu}$

(e) At 7-day age; $\sigma_1 = 0.4 f_{cu}$, $\sigma_2 = 0.4 f_{cu}$

(f) At 14-day age; $\sigma_1 = 0.2 f_{cu}$, $\sigma_2 = 0.1 f_{cu}$
Fig. 13. Comparisons of the proposed bond stress-slip models and other models with the experimental data under different load combinations at different curing ages for the low temperature curing at 0ºC.

Fig. 14 illustrates the relationship between $\alpha$ and the combination of lateral pressures for different curing temperatures. It can be seen that there is no direct relationship between $\alpha$ and the combination of lateral pressures (denoted by $\sigma_m$). Hence, $\alpha$ is independent of the lateral pressures. Previous studies [14,21] also confirmed that $\alpha$ is dependent on failure mode and simply defined two different constant values for it.

In this study, however, splitting failure did not occur. Thus, the mean value of the parameter $\alpha$ for all the tested specimens is taken. It can be seen that $\alpha$ varies from 0.47 to 0.71 with a mean value of
0.59. Similarly, by performing the regression analysis, the parameter $\beta$ can be estimated by using Eqs. (7) and (8) as follows, with respect to the curing temperatures of 0°C and 20°C. The correlation coefficients corresponding to the curing temperatures 0°C and 20°C are 0.63 and 0.57, respectively, which showed an agreeable numerical regression on $\beta$ according to the experimental data.

$$\beta = 0.509 - 0.035t - 2.25 \frac{\sigma_1}{f_{cu}} - 0.617 \frac{\sigma_2}{f_{cu}},$$  
for 0°C curing temperature \hspace{1cm} (7)

$$\beta = -0.016 - 0.028t - 1.313 \frac{\sigma_1}{f_{cu}} + 0.184 \frac{\sigma_2}{f_{cu}},$$  
for 20°C curing temperature \hspace{1cm} (8)

7 Conclusions

In this study, 150 cubic specimens have been produced for 50 groups of steel bar pull-out tests to investigate the influences of low curing temperatures on the bond behaviours of early age concrete under biaxial confining pressures. The experimental conditions covered the concrete curing ages of 1, 3, 7, 14 and 28 days, biaxial pressures varying from $0.1f_{cu}$ to $0.4f_{cu}$ with five loading combinations, and two curing temperatures of 0°C and 20°C. Based on the experimental results, the influences of low curing temperature, together with biaxial lateral pressures on the bond behaviours of deformed steel bars embedded in the early age concrete were investigated. The following conclusions can be drawn based on the experimental studies:

1. Low curing temperature significantly decreased the ultimate bond stress (bond strength) at very early curing ages. For a given biaxial lateral pressure combination of $\sigma_1 = \sigma_2 = 0.1f_{cu}$, the ratios of the ultimate bond stresses (bond strengths) for the specimens cured at 0°C to those at 20°C were 0.42, 0.89, 0.98 and 89.5 for the curing ages of 3, 7, 14 and 28 days, respectively.

2. Lateral pressures increased the ultimate bond stress (bond strength) between the concrete and steel rebar at 20°C curing temperature. However, the specimens cured at 0°C had various trends for different curing ages. The ultimate bond stress (bond strength) for the curing ages of 14 and 28 days increased with the increasing lateral pressures, while at the early curing ages of 3 and 7 days, lateral pressures had negligible effects on the ultimate bond stress (bond strength).
3. The bond slip corresponding to the ultimate bond stress (bond strength) increased steadily with the increasing curing age. However, the tests showed the largely scattered results under different combinations of lateral pressures.

4. An empirical model was proposed for the bond stress-slip relationship by using the regression analysis on the experimental data in this study. By comparing with the existing bond stress-slip models, the proposed model in this study showed better agreements with the experimental results, demonstrating the significant influences of low curing temperature and lateral pressures on the bond behaviours of deformed steel bars embedded in the early age concrete.

**Conflict of interest:** The authors declare that they have no conflict of interest.

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