Magazine of Concrete Research
Volume 67 Issue 2

Discussion
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Magazine of Concrete Research, 2015, **67**(2), 104–106
http://dx.doi.org/10.1680/macr.14.00223
Paper 1400223
Published online ahead of print 20/09/2014

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Discussion: Bond behaviour of deformed bars in self-compacting lightweight concrete subjected to lateral pressure

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Contribution by J. R. Martí-Vargas

The paper by Wu *et al.* (2013) presents interesting experimental results, empirical formulae and a model to characterise the bond behaviour of deformed bars in self-compacting lightweight concrete subjected to uniaxial and biaxial lateral pressures with different pressure ratios. The authors should be complimented for producing this detailed paper, which was of interest for the discusser, who would like to offer some comments for the authors' consideration and response, mainly about test parameters, normalised ultimate bond stress (UBS), slip at UBS and the ratio between residual and ultimate bond stress.

It is generally recognised that UBS increases with an increase in uniaxial lateral pressure. The authors have found that UBS increases with a rise in p_2, but that it is independent of p_1, p_2 and p_1, with the uniaxial lateral pressures being parallel (p_2) and perpendicular (p_1) to the transverse rib of the deformed bars. However, it seems that this disagrees with the results shown in Figure 7, which indicates, as stated by the authors, that lateral pressure has a marked effect on bond strength. Both normalised UBS (Figure 8(a)) and slip at UBS (Figure 12(a)) appear to be independent of the p_1/f_{cu} ratio (f_{cu} = concrete compressive strength), whereas these parameters are influenced by p_1 as observed in Figure 8(b) and Figure 12(b), respectively: for the same p_2/f_{cu}, different values of the normalised UBS and slip at UBS are shown, based on different p_1 values. That is, it seems that UBS also depends on p_1. It is noteworthy that lateral pressure influences not only the bond stress–slip behaviour of the deformed bars, but also concrete compressive strength. Therefore, an analysis of the results based on lateral pressure and normalised UBS related to the actual concrete compressive strength for the corresponding confinement conditions is suggested.

Moreover, in the discusser's opinion, lateral pressure p_1 should be more effective than p_2 regarding the bond stress increases, as follows: p_1 is perpendicular to the ribs, which gives a well-confined result; however, p_2 is parallel to the ribs, which gives a more poorly confined result because the concrete specimen expands following an orthogonal direction owing to the Poisson effect.

The authors propose several equations for normalised UBS, but only one was finally selected because of the uncertain orientation of the transverse ribs in practical engineering. However, no parameter in these equations is related to the ribs' orientation. Experimental constants have been used in bond models by other authors (Viula *et al.*, 2013). Can the authors provide some explanation about this to offer a better understanding?

In addition, for the selected equation, a limit value of $3{\cdot}0\ \mathrm{MPa}^{0{\cdot}5}$ has been established for $c/d > 4{\cdot}5$. The discusser notes that a value of $2{\cdot}8\ \mathrm{MPa}^{0{\cdot}5}$ results for $c/d > 4{\cdot}5$, whereas $3{\cdot}0\ \mathrm{MPa}^{0{\cdot}5}$ corresponds to $c/d > 4{\cdot}8$. This can be related to an assumption considered in *Model Code 2010* (FIB, 2010), which perhaps has not been noted by the authors: good confinement results when c/d is not less than 5 (García-Taengua *et al.*, 2011).

The ratio between residual stress and UBS (k_{r}) is shown in Figure 14, which plots k_{r} against c/d. As observed, k_{r} ranges from 0·2 to 0·5. In the discusser's opinion, the analysis provided by the authors, that k_{r} is independent of lateral pressure and is proportional to c/d, is not supported by Figure 14. Perhaps some information is missing: lateral pressure details are not included, and k_{r} presents lower values for the intermediate c/d when only 'shale' points are considered. Can the authors offer further details on this topic?

Authors' reply

The authors would like to thank the discusser for the interest in this paper and for the valuable comments and suggestions. The authors' responses to the questions raised by the discusser are addressed item by item below.

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As noted by the discusser, this paper focuses on the effect of lateral pressure on the bond behaviour of deformed bars embedded in self-compacting lightweight concrete. As shown in Figure 7, the normalised bond strength has, as a whole, an increasing tendency with lateral pressure, although a small proportion of the experimental results suggested that it is independent of p_1. Therefore, the authors still concluded that lateral pressure has a marked effect on the bond strength. In fact, the normalised bond strength is also affected by other factors, such as the bar diameter and cover depth.

It seems inappropriate to conclude from Figure 8(b) that the normalised bond strength is dependent on p_1 for specimens subjected to uniaxial lateral pressure, as suggested by the discusser. Excepting those data for the specimens under $p_2 = 0$, the data shown in Figure 8(b) correspond to the specimens under $p_1 = 0$. This indicates that it is difficult to obtain any reasonable information on the relationship between $\tau_u/\sqrt{f_{cu}}$ and p_1 because p_1 is fixed to zero. From Figure 8(a), it can be seen that $\tau_u/\sqrt{f_{cu}}$ is independent of p_1.

The authors agree with the discusser that the lateral pressure p_1 should be more effective than p_2 in increasing the bond stress, only on the condition that the specimen fails in splitting. However, in the experiment, the specimen fails in mixed splitting/pull-out and pull-out when lateral pressure is applied. The failure modes are characterised by the pulling out of bars from the specimen and the crushing of concrete between adjacent ribs. In such a case, the bond capacity depends mainly on the strength of concrete in the debonding zone, as explained by Xu *et al.* (2011). Figure 17 gives a brief stress analysis. When p_2 is applied, the concrete in the debonding zone is in compression in three directions and therefore the bond strength increases. When p_1 is applied, however, the bond strength is not significantly affected by p_1 because the concrete is in compression in two directions and in tension in the third direction.

In this paper, the equations to determine the bond strength of self-compacting lightweight concrete (SCLC) specimens were derived through numerical regression based on the experimental results. The authors have taken several factors into account, such as the compressive strength of concrete, bar diameter, cover depth and lateral pressure. The discusser's query mainly focuses on two influential factors: the compressive strength of concrete and rib orientation. The authors share the discusser's viewpoint on the influence of lateral pressure on the compressive strength of concrete, which in turn influences the bond behaviour; however, the pull-out specimen can be considered as a structural element, consisting of concrete and reinforcing bars. It seems more reasonable to use the compressive strength of concrete without lateral pressure.

The effect of the rib orientation on the bond behaviour has also been considered in the experiment and the related equation, that is Equation 2, was obtained. Since bars are located with random orientation in practical engineering, only the bond strength in the most unfavourable case was considered; that is, the normalised bond strength has no improvement by lateral pressure. Therefore, the rib orientation was not considered as a dominant factor in

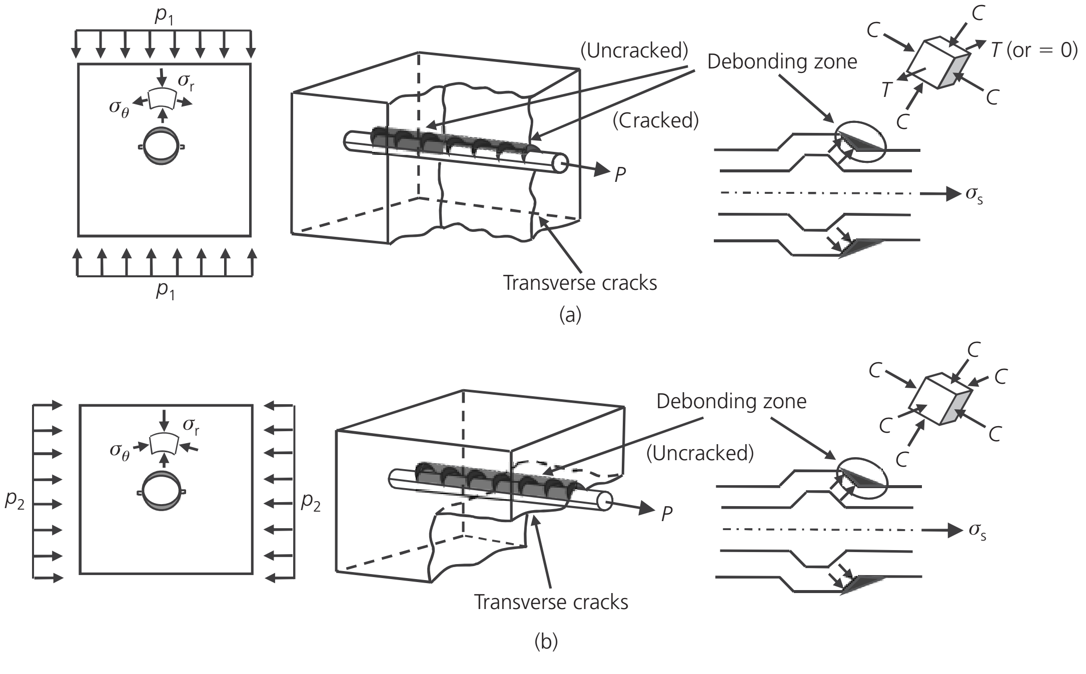

Figure 17. Stresses in the debonding zone of specimens subjected to: (a) p_1 and (b) p_2

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Equation 3 in this paper, although Equation 3 is possibly conservative for practical use.

As noted by the discusser, $\tau_u/(f_{cu})^{0\cdot5}$ is not continuous at $c/d = 0\cdot45$ in the original paper. Therefore, Equations 3 and 4 are revised as follows.

For $c/d \leqslant 4\cdot8$

$$\frac{\tau_u}{(f_{cu})^{0\cdot5}} = 0\cdot50 + 0\cdot52\frac{c}{d} \tag{3}$$

and for $c/d > 4\cdot8$

$$\frac{\tau_u}{(f_{cu})^{0\cdot5}} = 3\cdot0\ \text{MPa}^{0.5} \tag{4}$$

k_r represents the ratio of the residual to ultimate bond stress and is listed in Tables 4 and 5 for different lateral pressures and c/d.

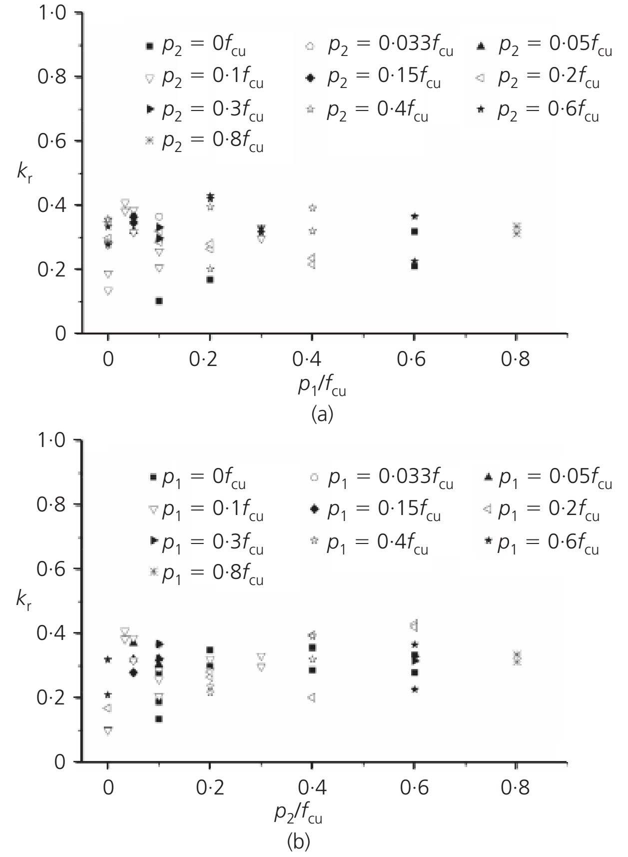

Figure 18. k_r for specimens subjected to: (a) p_1 and (b) p_2

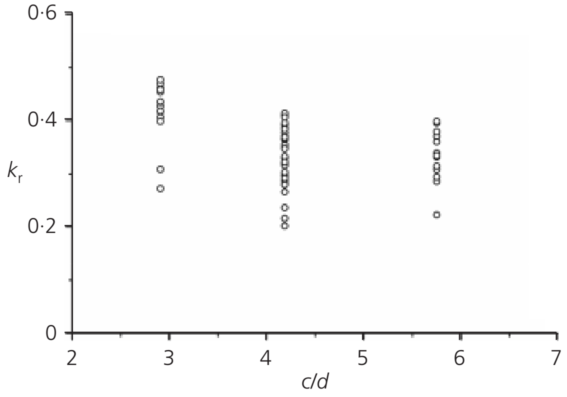

Figure 19. Relationship between k_r and c/d for specimens made with shale

k_r is considered to be independent of p_1 or p_2. Owing to the large scatter of experimental data, the relationship between k_r and lateral pressure is not adequately clear, as shown in Figure 18. But it was found that k_r is approximately proportional to c/d. From Figure 16, it can be seen that the k_r-based bond–stress curve agrees reasonably well with the experimental results. Therefore, Equation 7 can be used to formulate the bond-stress model.

Figure 19 gives the value of k_r of the specimens made with shale only. It seems that k_r has a progressively descending trend with c/d. The lower value of k_r for the intermediate value of c/d is not sufficiently obvious and is possibly attributed to the scatter of experimental data.

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