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Stress-strain characteristics of concrete confined in steel binders*

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The authors seem to have started with the preconceived notion that increases in the strength and deformability of confined concrete due to lateral reinforcement are proportional to the index $p_b f_y / f'_c$. There does not seem to be any conclusive evidence indicating that this is necessarily so. A recent experimental investigation carried out at the University of Waterloo⁽¹⁾ indicated that increases in the strength and peak strain values of confined concrete are inversely proportional to the square root of concrete strength, and not to concrete strength itself, as postulated in the paper. It should also be noted that the postulate is not strongly supported by Figures 6 to 9, in which the correlation between experimental points and the straight lines fitted to them is not very good. In Figure 6, the experimental points of Richart et al. (reference 4 of the paper) seem to fit the analytical straight line better than the authors' own experimental points. But Richart's experimental data were subjected to a process of conversion which may not have been entirely justified.

I also have reservations as to the validity of the authors' comparison between equations 1 and 2 and equation 3 which was derived from the test results of Szulczynski and Sozen (reference 7). In the field of concrete, a comparison of test results, obtained under conditions which may not have been exactly similar, is not usually valid. The wide divergence between the two straight lines which were fitted in Figure 8 to the

test results of references 7 and 10 would amply justify this comment.

The constants in equations 5, 6, 8 and 9 were derived by the authors from the stress-strain equation proposed by Desayi and Krishnan (reference 18). I believe that this equation has a serious drawback. It is well known that the descending branches of concrete stress-strain curves become steeper as the concrete strength increases. But the slopes of the declining branches of curves given by the stress-strain equation of Desayi and Krishnan do not vary with concrete strength. Moreover, the magnitude of slope is such that the descending branches of these curves can represent true concrete behaviour for very low strengths of concrete only.

I found the theoretical analysis in the paper extremely interesting. There are two important differences between the confinements due to lateral reinforcement and hydrostatic pressure. Firstly, confining forces are applied by lateral reinforcement along discrete lines and vary along these lines as well as between them. Secondly, confinement due to lateral reinforcement is a function of longitudinal deformations, whilst hydrostatic pressures are independent of them. The authors get round the first difference by considering, instead of the actual lateral reinforcement, a continuous thin-walled cylinder of a volume equivalent to that of the lateral reinforcement. They get round the second difference by considering only the maximum lateral pressure exerted by lateral reinforcement, so that the stress in the reinforcement remained

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constant and equalled the yield strength. Whilst this underlying basis of the analysis is clear, I do not quite see how f_c' in equation 17 becomes equal to 3945 lb/in² from a comparison with equation 14. The bracketed term in equation 14 is raised to the power 0.73. Would the authors please explain this? They have rightly pointed out that, whilst circular spiral reinforcement develops tension only, rectangular spirals and stirrups are subject to bending as well as direct tension. The indirect way of determining the lateral pressure exerted by rectangular binders, however, appears to be rather too simplistic.

Before concluding this discussion, I would like to point out that an understanding of the behaviour of confined concrete, in itself, does not lead to a full knowledge of the behaviour of reinforced concrete in compression. In practice, the reinforcing steel in a concrete member must be protected against fire and corrosion by an adequate thickness of concrete. This concrete cover, when in compression, also acts to provide structural strength. The protective cover and the

core confined within ties exhibit different mechanical properties, as demonstrated by the spalling off of the cover at high deformations, while the core remains intact. It can reasonably be assumed that, at any stage of loading, the cover and the core undergo the same deformations. However, I have demonstrated elsewhere^(2,3) that the cover is less effective than the core in resisting loads. Because of this lower load-carrying capacity of the cover, the over-all strength of a compression member reinforced with ties may be less than that of an identical plain concrete member. I have also shown^(2,3) that the closer the tie spacing and the larger the amount of lateral reinforcement, the less is the effectiveness of cover in resisting loads, and that this effectiveness increases with an increase in cover thickness. These conclusions, however, still remain largely qualitative. To gain a full understanding of the behaviour of reinforced concrete in compression, quantitative conclusions relating the effectiveness of cover to tie diameter, tie spacing, cover thickness, etc., will have to be reached through experiments.

Reply by the authors

We thank Mr Ghosh for his interest and comments on our paper.

While searching for a non-dimensional factor which could define the confinement quantitatively, which took into account both the physical and the strength parameters of the confining and confined media and which was fairly simple and satisfactory for use in concrete design work, we arrived at the factor $(p_b - \bar{p}_b)f_y/f_c'$. The correlation coefficients of the straight lines fitted in Figures 6, 7 and 9 (equations 1, 2 and 4) respectively being 0.87, 0.83 and 0.95 and those for the equations 5, 6, 7, 9 and 10 being 0.93, 0.90, 0.88, 0.79 and 0.91 respectively, we felt that these values were reasonably good for concrete studies. In studies where greater accuracy is desired, the confinement index could be defined as $(p_b - \bar{p}_b)^m(f_y/f_c')^n$ where m and n are positive constants and the magnitudes of m and n are determined for the statistical best fit of a given set of test results. Such a general definition could accommodate the experimental observation quoted by Mr Ghosh, namely that the increase in strength and peak strain values of confined concrete were inversely proportional to the square root of concrete strength, and at the same time retain the non-dimensional nature of the confinement index. For our test results, we felt it satisfactory to retain $m = n = 1$, when we found that the test results of Richart et al. (reference 4 of the paper) were also fitting in well. As regards the comparison between our own results and those of reference 4 (Figure 6), the conversion of the latter results is explained in the footnote on page 178, and we have no reason to feel that the process of conversion is unjustifiable.

The wide divergence between the test results of references 7, 10, 8 and 9 shows clearly that the strength and behaviour of concrete confined in stirrups requires a thorough investigation. However, in concrete studies (as in any other study), comparison of test results of different investigators becomes necessary and this can be done as long as the different conditions under which the tests were made are taken into account. The reasons which led to the choice of the results of only reference 7 for purposes of comparison with confinement due to circular and square spirals have been indicated already in the paper. We agree that the results of a single investigation in which the three types of confinement had been exhaustively investigated would have led to more valid comparisons.

We agree with Mr Ghosh that it would have been better if the constants of equations 5, 6, 8 and 9 had been obtained by using the stress-strain data of unconfined specimens. However, we feel that the constants now obtained, by using the stress-strain relationship of reference 18, hold fairly well for the normal-strength concretes usually adopted in reinforced concrete work—they may be slightly different for high-strength concretes.

In equation 14, if the bracketed term is expanded, we get a constant term as 3945 lb/in² and variable terms of functions of S_3 . Then, comparing this with equation 17, we find $f_c' = 3945$ (the rest of the variable terms being comparable to the second term of equation 17, which is also a function of S_3').

We agree with Mr Ghosh that the effect of cover on concrete confined in steel binders needs thorough investigation. While specimens having circular spiral

and square spiral binders were being tested, it was noticed that the specimens showed peeling of the cover even before ultimate, and there was considerable spalling of the cover by the time the ultimate was reached; it was only the core that was intact at ultimate and beyond. (This may be observed in the tested specimens shown in Figure 2.) As the compressive load on a bound concrete specimen increases, the increasing lateral strain of the core concrete causes the binder to expand which, in turn, pushes away the cover outside

the binder—this may also lead to a narrow zone of separation between the cover and the binder. The cover thus separated from the parent mass cannot withstand the stress which it might be carrying earlier and hence it peels and spalls. It is quite possible that, up to about 60 to 70 % of ultimate, cover also is associated in withstanding the external compressive force, but beyond this stage it could be only the core that is effective, which has also been observed by Mr Ghosh.

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