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Influence of Shear on Rotation Capacity of Reinforced Concrete Members Without Shear Reinforcement
by Rui Vaz Rodrigues, Aurelio Muttoni, and Miguel Fernández Ruiz

Discussion by Andor Windisch

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The authors have investigated the influence of shear on the rotation capacity of one-way slabs without shear reinforcement, presenting and discussing the results of 11 slab strips, 10 of them failing in shear before and after yielding of the flexural reinforcement.

The authors refer to the traditional expression of rotation capacity as a function of the depth of the compression zone and the ductility of the flexural reinforcing steel, as given in most theoretical models and codes of practice. The results of their test specimens can neither prove nor disprove these assumptions, as the cross sections are double reinforced—that is, the tensile and compressive reinforcement are identical. Eight specimens had cold-worked reinforcement and at the remaining three, hot-rolled flexural reinforcement was applied: no attention was paid to the bond characteristics, which are the most important influencing factors of the ductile behavior of a reinforced concrete (RC) member.

The measurements of relative displacement between lips of critical shear crack shown in Fig. 10 are extremely interesting and important: the authors declare correctly that the evolution of the relative displacement along critical shear crack absolutely follows the rules of kinematics; incremental increase occurs perpendicular to the actual radius to the actual tip of the crack. As shown in Fig. 10(b), Δu increases up to 2.2 mm (0.087 in.) beyond $V = 0.65V_{max}$. Yielding of the longitudinal reinforcement occurs at $0.85V_{max}$. Tangential relative displacements Δv occur after yielding only; nevertheless, the existence of this component depends on the actual relative position of the crack tip only, not on the yielding itself. Advocates of the aggregate interlock agree that no shear stresses may develop along the crack without Δv displacements, and shear stresses do not increase without increases in the stress normal to the crack. Moreover, it decreases with increasing normal displacements. Thus the question arises: what is the source of the increase of the shear force between 0.65 and $1.0V_{max}$, or between 0.85 and $1.0V_{max}$, respectively? Other specimens have also shown shear crack widths of 1 to 3 mm (0.04 to 0.12 in.), 6 mm (0.24 in.), 30 mm (1.2 in.), and even 60 mm (2.4 in.), respectively. How does the aggregate interlock function under these conditions?

In Fig. 12 (as well as in other figures in their previous papers), the authors refer to the detrimental development of the critical shear crack along the theoretical (straight or curved) compression strut that leads to the failure of the inclined compression strut and that of the member. The compression strut is "prestressed" through the compressive force in it; hence, how could the shear crack penetrate this strut? The critical shear crack model contradicts both the variable angle stress field and the modified compression field theory (MCFT). This could actually be considered an advantage of the critical shear crack theory (CSCT) model.

The beams with the cold-worked and the hot-rolled flexural reinforcement bars show very different rotation capacities, certainly due to the better bond characteristics of the latter. The authors state, "Specimens SR2 and SR11 failed in shear near the intermediate support before yielding of the flexural reinforcement and in an extreme brittle manner." The last column in Table 3 reveals that Eq. (3) substantially overestimates the shear failure load on the unsafe side: how will the authors prevent this dangerous situation? Moreover, the validity of Eq. (3) and (7) cannot be checked with the calculated values given in Table 3. For the calculation of the $V_{R,\ model}$ value, the authors (in a quite unusual manner) insert the measured ψ_R values, thus blurring the boundaries between theory and test.

It could be sensible to split Eq. (6) according to the bond characteristics of the flexural reinforcement: although the ultimate shear forces are quite identical for the relevant members, the predicted shear strengths (taking into account the measured ψ values, similar to the authors) are 1.7 to 3 times higher for slab strips with cold-drawn reinforcement. In conclusion 4 of the paper, the authors propose to neglect this difference: is it sensible and economical to do this? The estimation for the width of the critical shear crack, Eq. (5), does not properly reflect the better cracking behavior of members reinforced with high-bond reinforcing bars. Evaluating the $V_{R,\ test}/V_{R,\ model}$ values given in Table 3, the mean value for the slabs with cold-drawn reinforcement is 1.06, $v = 0.11$. The same values for slabs with hot-rolled reinforcement are 1.28 and 0.30, respectively. Here, systematic deviations can be detected; a splitting would be sensible.

Checking the interdependence of the ratios $V_{R,\ test}/V_{R,\ model}$ and the related (measured) ψ_R and ψ values according to Eq. (7), respectively, and then both ψ values to each other: in all cases, poor correlations can be found. This reconfirms the discusser's conclusion related to a recent paper[18] of the authors: the rotation of slab is a poor independent variable for determination of the shear capacity of RC members. The product ψd does not properly account for the width of the critical shear crack.

In the case of the tested double-reinforced cross sections, the M_{flex} values cannot be calculated as given in the paper; thus, Eq. (7) for the rotation capacities is false, too. Whether Eq. (6) and (7) for V_R and ψ_R properly reflect the influence of the aggregate size or not cannot be determined, as all test specimens were made with 16 mm (0.63 in.) maximum size gravel.

Conclusions 1 and 2 are platitudes. In conclusion 3, the first sentence should read as follows: Failures in shear after yielding of the flexural reinforcement develop due to the fact that the width of the shear cracks increases, resulting in a reduction of the strength of the various shear-carrying mechanisms of the member and in increasing rotations. The rotation is not the cause but the result of the cracks and their width. The second sentence is not clear either: how can, in the case of a given slab-geometry (that is, *a*/*d* ratio), the load and the strain in the flexural steel increase and simultaneously the shear force stay constant or decrease? In conclusion 4, the pronounced differences between the measured rotation capacities of test specimens with cold-worked and hot-rolled reinforcement, respectively, contradict this conclusion. Regarding conclusions 5 and 6, the model is not consistent. It does not assist the designer to distinguish even the most simple but crucial case, whether the slab fails before or after yielding of the flexural reinforcement.

REFERENCES

18. Ruiz, M. F.; Muttoni, A.; and Kunz, J., "Strengthening of Flat Slabs Against Punching Shear Using Post-Installed Shear Reinforcement," *ACI Structural Journal*, V. 107, No. 4, July-Aug. 2010, pp. 434-442.

AUTHORS' CLOSURE

The authors would like to thank the discusser for his interest in the paper. Detailed replies to his questions and suggestions are given as follows:

- Ordinary reinforcement was used, whose bond properties are widely referred to in the literature. The discusser should also note that bond is a key parameter for the rotation capacity of plastic hinges, provided that they fail in bending (rupture of steel in tension). Shear failure develops due to an unstable propagation of a critical shear crack, however, and the influence of bond is much more limited. The geometry of the reinforcement ribs is nevertheless fully detailed in the test report.[11]
- Aggregate interlock can be mobilized through the critical shear crack as the opening of the crack is variable (large crack widths near the flexural reinforcement but very limited crack widths near the compression zone) and regions of the small crack width opening are always present. Figure 10(b) shows the evolution for a given point, where the slip component Δv develops after the crack changes its relative center of rotation (no longer being aligned with the direction of the crack at the point investigated). Other points of the crack (closer to the flexural reinforcement in this case) have, however, mobilized slip components and thus aggregate interlock at this level of load. A detailed analysis of the shear force carried across the critical shear crack has been detailed elsewhere.[10]
- The fact that the critical shear crack develops through the theoretical compression strut (Fig. 12(b)) means that the strength of the plastic load-carrying mechanism for a beam cannot be attained; however, the actual state of stresses when such critical shear crack develops is different to that shown in Fig. 12(b). This has been explained elsewhere.[9] After first cracking, a beam develops a number of shear-carrying mechanisms (aggregate interlock, dowel action, cantilever action) leading to the development of cracks whose shape is actually that of the critical shear crack. Once such a critical shear crack develops, the strength of the theoretical compression strut required according to the theory of plasticity is diminished and thus the strength with respect to the predictions of the theory of plasticity.[8,9]
- The different behavior observed for specimens with hot-rolled and cold-worked steel are, in the authors' opinion, due to the rather different hardening shape rather than to bond properties (with hot-rolled steels leading to larger openings of the cracks when yielding of the flexural reinforcement develops, thus leading to larger rotations, due to the presence of the reinforcement's plastic plateau).
- As the discusser may have noted in Fig. 13, the proposed equation is plotted in a dotted line (not solid) for these tests. This is due to the fact that for Tests SR2 and SR11, no yielding of the reinforcement developed; thus, equations according to the CSCT developed elsewhere[9] apply to calculate strength. With respect to checking the validity of the failure criterion by using measured values of rotation, it seems perfectly correct to the authors, being the same technique as the one used, for instance, for checking the suitability of the failure criterion of the CSCT in punching. (A different matter is getting a prediction of the load-rotation curve, which is not dealt with in the paper; references are made to the literature.)
- The authors agree with the discusser that two formulas can be proposed. For design purposes, however, where the type of steel is normally not known, it is sufficient to adopt the proposed law (applicable for cold-worked steel and conservative for hot-rolled steel).
- Checking at the different correlations (Fig. 13) indeed reconfirms[18] that rotation is an excellent parameter explaining (and correlating) the observed result.
- The authors are in disagreement with the statement that the equation cannot be used for sections others than with the same reinforcement on top and bottom. Other sections and reinforcement layouts will lead to different rotations and failure loads, but the relationship between them (failure criterion) is governed by concrete and the proposed equation will still apply.
- Conclusions 1 and 2 are judged as important and they have been unclear topics to most designers and researchers for a number of years. Conclusions 3 to 6 are correct as stated in the paper (please refer to the previous points).

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Fatigue Behavior of Reinforced Concrete Beams with Corroded Steel Reinforcement

by Wei-Jian Yi, Sashi K. Kunnath, Xiao-Dong Sun, Cai-Jun Shi, and Fu-Jian Tang

Discussion by Ping Gu, Cong Zhou, and Shiming Chen

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The corrosion of steel reinforcement severely decreases the service life of reinforced concrete (RC) structures. Corrosion leads to a reduction in the cross-sectional area of the reinforcing steel (or mass loss) and a loss of bond between the reinforcing steel and the concrete. Coupled corrosion-fatigue deterioration results from the combined action of cycling stresses in corrosive environments. The discussers appreciate the authors' comprehensive work illustrating the