Closure to "Strength Analysis of Steel-Concrete Composite Beams in Combined Bending and Shear" by Qing Quan Liang, Brian Uy, Mark A. Bradford and Hamid R. Ronagh

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The authors wish to thank the discusser for his interest in the paper. The discusser raises four points in his discussion. First, he asks how the shear connection stiffness in the finite element model was derived which should not be the stiffness in real beams. Second, he points out that the degree of shear connection should substantially decrease with a decrease in the span for the same section beam while keeping the ultimate longitudinal force resisted by shear connectors unchanged. Third, he argues that the three-dimensional beam element used to model discrete stud shear connectors could simulate local stress distribution in concrete around the stud shear connectors, and then he demonstrates that the finite element results presented in the discussed paper compare very well with experimental results given by others. Fourth, the discusser wants the authors to clarify the stress-strain curve used for steel in the finite element model.

For the first point, the authors clearly indicated in the discussed paper that the cross-sectional area of the beam element was modified to make it equivalent in both strength and stiffness to the actual stud shear connectors in the composite beam. This was verified by a comparison of the load-deflection curve obtained from the finite element analysis with experimental data in Fig. 6 in the paper. The figure indicates that the stiffness of the shear connection modeled using finite elements was almost the same as the stiffness of the shear connection in the real beam tested by Chapman and Balakrishnan (1964). The ultimate strength of the composite beam predicted by the finite element model was 95.3% of the experimental value.

The composite beam tested by Chapman and Balakrishnan exhibited full shear connection, which means that the shear connection is so strong that additional stud shear connectors will not increase the flexural strength of the composite beam. The span to depth ratio (L/D) of the original composite beam was 11.6 and the beam was a flexural member whose strength can be determined by the flexural beam theory. By reducing the span of the composite beam from 5.5 m to 0.8 m, the span to depth ratio of the beam was reduced from 11. 6 to 1.7 and the composite beam changed from a flexural member to a non-flexural member. The flexural beam theory no longer applies to the design of the non-flexural composite beam. As described in the discussed paper, the shear load in the deep composite beam $(L/D=1.7)$ was transferred to the supports by a strut-and-tie model (Liang 2005; Liang et al. 2000). When the span of the composite beam was reduced, the load transfer mechanism in the beam was changed and the longitudinal force resisted by the stud shear connectors was also reduced. For the deep composite beam with $L/D=1.7$, the load was transferred directly through two inclined struts to the supports and the tensile force in the steel beam (tie) was significantly reduced when compared with that in the beam with a span to depth ratio of 11.6 (Liang et al. 2000). The steel section in the deep composite beam might not yield when the composite beam failed in shear or in the crushing of the concrete in the struts. It can be seen that the longitudinal force F_u is not a constant and will vary with the changes in the span to depth ratios of composite beams. The full shear connection of the composite beam was approximately maintained in all shortened beams as shown in Fig. 8 in the paper.

The stud shear connectors in composite beams are discrete in nature. The three-dimensional beam elements were therefore used in the finite element model to simulate the discrete behavior of stud shear connectors in composite beams. This model is an improvement to the continuous shear connection model. The discusser demonstrates in Fig. 1 that the vertical shear capacity of composite beams with various span-to-depth ratios predicted by the authors' finite element model compares very well with experimental results presented by Nie et al. (2004). The discusser has further verified the finite element model and the results presented by the authors. The authors wish to thank the discusser for his additional work on this.

Based on recent test results presented by Kemp et al. (2002), an idealized bilinear stress-strain curve was used in the finite element model to account for the strain hardening of structural steels. The ultimate strain of 0.25 was assumed for structural steel in the analysis and the experimental values of the yield strength and ultimate strength were used in the analysis for the steel section as described in the discussed paper. The discusser should not assume that the secant modulus of the steel was taken as one tenth of the initial modulus. The design model for strength interaction given in Eq. (11) in the discussed paper can be used to determine the ultimate strengths of simply supported composite beams under combined bending and shear. This approach considers the contributions from the steel web and concrete slab, the pullout capacity of stud shear connectors and web shear buckling as described in the paper. It appears that the transformed equation presented by the discusser is not correct.

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