Discussion of "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

October 2005, Vol. 131, No. 10, pp. 1593–1600
DOI: 10.1061/(ASCE)0733-9445(2005)131:10(1593)

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The discusser appreciates the authors' comprehensive work to evaluate the ultimate strength of composite beams in combined bending and shear based on a finite-element analysis. Design models for vertical shear proposed for design of the simply supported composite beams in combined bending and shear should provide an economical solution when the concrete slab connected to the top steel flange contributes to the shear strength of the beam as far as the shear connection is efficient. To make the finite-element parametric analysis and design philosophy interpretable, however, the definition of shear connection degree adopted in the study should be clarified.

Shear Connection Modeling and Shear Connection Degree

In the paper, to assess the ultimate resistance of a simply supported composite beam, a three-dimensional beam element was used to model discrete stud shear connectors, and the studs were assumed to connect the middle plane of the concrete slab and the top steel flange of the steel beam (both were modeled by shell element). This should be crucial in the finite-element study and raise a question how the shear connection stiffness in the analysis model was derived, which should not be the stiffness in real beam or that simply from push-out test.

Accordingly, the full shear connection for a composite beam is known as being sufficient shear strength provided by the shear connectors in the critical shear span at the interface between the concrete slab and the steel beam to enable full plastic strength in the steel beam section. Let P_{st} be the design shear resistance of each stud; n be the available number of studs in the critical shear span; n_f be the number of shear studs capable of being a full shear connection composite beam; and F_u be the ultimate longitudinal force resisted by the shear connectors. The required number of shear connectors within the critical shear span to enable full shear connection is determined as

$$n_f = \frac{F_u}{P_{st}} \tag{1}$$

A partial shear connection composite beam occurs if $n < n_f$. The degree of shear connection denoted as $\beta = n/n_f$ should reflect the extent of flexural plasticity developed in the steel beam section. This however is not clarified in the author's finite-element analysis.

In the paper, a parametric study was carried out by varying beam span from 0.8 m to 5.5 m, corresponding to the moment/shear ratios from 0.4 to 2.75 m, being cut from the composite beam tested by Chapman and Balakrishnam (1964). As it is not emphasized that number of shear connectors were changed, the discusser does not agree that "the degree of shear connection was approximately same for all cases" as the authors stated. If the spacing of stud shear connectors remains the same for all cases, the number of stud shear connectors and hence the degree of shear connection should decrease as the shear span decreases. For the sample beam, the plastic neutral axis (PNA.) was lying in the slab, so that the ultimate longitudinal force in the critical shear span resisted by the shear connectors capable of full shear connection is $A_s f_{sy}$ (A_s is area of steel beam section and f_{sy} is the yield strength of structural steel), or saying 2189.3 kN derived based on the provided geometry and material properties, as far as the shear studs are ductile. Therefore the number of shear connectors would change from 102 for a full span of 5.5 m to 18 or 20 for a span 0.8 m if spacing and number of rows of stud shear connectors remains the same; this should lead a sharp reduction in the shear connection resistance so that there was a substantial decrease in the degree of shear connection.

Shear Span/Depth Ratio against Vertical Shear Force

From Fig. 7, the load is approximate 1600 kN with moment/shear span equal to 0.4 m. A vertical shear force of 800 kN approximately is greater than V_s (shear capacity of steel web, saying 433.9 kN for the sample beam), owing to contribution of concrete slab, which is governed by either the shear strength of slab [determined by Eq. (7)] or the pullout capacity of stud shear connectors [determined by Eqs. (8) or (9)]. It is believed that pullout failure of stud shear connectors occurred in the beam, as the shear strength of slab is 844.2 kN in the case. However, it should be argued that the 3D beam element used to model discrete stud shear connectors could simulate local stress distribution in concrete around the stud shear connectors.

The load is approximate 1,250 kN when α is 1.0, corresponding to a vertical shear force 625 kN. The vertical shear force drops approximately to 390 kN when α is 1.75. The vertical shear force based on the finite-element study is drawn against span/depth ratio in Fig. 1. In Fig. 1, the vertical shear force divided by V_w, the shear capacity of the web, in accordance with AISC specifications (1999) is in a nondimension form. Test results of simply supported composite beams reported by Nie (2004) are also drawn in the figure. The finite-element results are slightly smaller than the test results, so that they are on the safe side. It is noticed that when the shear span/depth ratio is greater than 4, the vertical shear force at the ultimate state will be approximate to or less than V_w, the shear strength of steel web, so that the flexural failure will govern. When the shear span/depth ratio is less than 4, shear strength contribution of concrete slab should be considered in assessment of load-carrying capacity of a composite beam.

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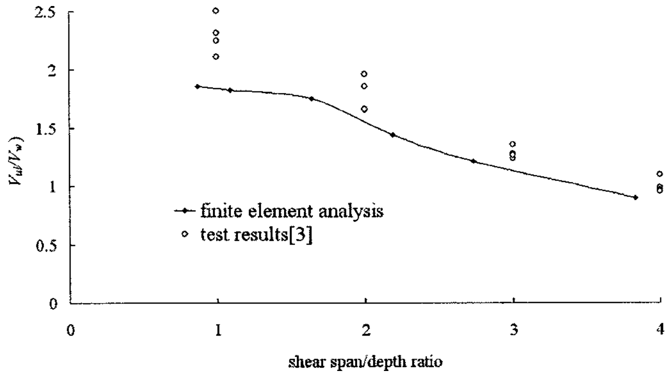

Fig. 1. Vertical shear force varying with shear span/depth ratio

Failure Patterns and Design Model for Strength Interaction

In the paper, it is noticed that the composite beam failed by flexural when the moment/shear ratio was high and failed by shear when the moment/shear ratio was low, such as when $\alpha = 0.4$ or 0.5. This, however, was not clear enough to distinguish shear failure patterns in concrete or steel; for instance, shear buckling of steel web may also initiate when the span/depth is low.

A bilinear stress-strain curve was adopted for steel in the finite-element study. As the ultimate strain of steel is taken as 0.25, it may lead a very high stress (saying approximate 5,100 $\mathrm{N/mm^2}$) at the ultimate state of steel flexure, if the second modulus is taken as one tenth of initial modulus. This should differ from the observation of a tensile sample test, that the maximum stress does not occur at the maximum strain. Could the authors clarify the maximum strain developed in the steel at the ultimate state, and what effect should it affect on the behavior of the composite beams?

Eq. (11) of the paper defines a design curve agree well with the parametric study. It can be rewritten as

$$M_u = M_{uo} \sqrt[6]{\frac{1}{1 + (M_{uo}/\alpha V_{uo})^6}} \tag{2}$$

where α = moment/shear ratio. Eq. (2) reflects the ultimate moment decreases with α, the moment/shear ratio so that the load carrying capacity of the beam can be calculated as far as the M_{uo} and V_{uo} are known. In initial design, it is more likely to use span/depth ratio as shown in Fig. 1, to assess the potential failure that might occur; this, however, is not obvious in Eq. (2) and in Eq. (11) of the paper.

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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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DOI: 10.1061/(ASCE)0733-9445(2005)131:10(1593)

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The writers wish to thank the discusser for his interest in the paper. The discusser raises four points. 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 writers to clarify the stress-strain curve used for steel in the finite-element model.

For the first point, the writers 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 (1964) 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 nonflexural member. The flexural beam theory no longer applies to the design of the nonflexural composite beam. As described in the discussed paper, the shear load in the deep composite beam $(L/D = 1.7)$ was trans-

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ferred 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 3D 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 of his response that the vertical shear capacity of composite beams with various span-to-depth ratios predicted by the writers' 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 writers. The writers 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 original 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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