CHAPTER 10

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Summary

Twenty-four solid slab push-out tests, 93 composite slab push-out tests, and three composite beam tests were conducted to study the strength of welded headed shear studs. The results were compared with predictions that were made using several existing stud strength prediction models, including those by AISC (*Load* 1993), Canadian Standards Association (*Steel* 1994), Eurocode 4 (*EN* 2001), and Johnson and Yuan (1997). All of the models evaluated were either unconservative in their predictions or were too complex for practical use.

These evaluations showed that a new stud strength prediction model was needed for studs welded through steel deck. Evaluation of 202 push-out tests performed at VT and elsewhere were used to form the model, which includes, as parameters, the position of the stud within the deck rib, the number of studs per rib, the cross-sectional area of the stud, and the stud tensile strength. Beam tests were used to verify the accuracy of the model, and from these tests, a resistance factor for the strength of studs in composite beams was calculated.

10.2 Conclusions

The solid slab push-out test data resulted in these conclusions:

1. The effect of flange thickness for *d/t* ratios less than 2.7 had no effect on the stud strength.
2. The steel/concrete interface plays a significant role in the *apparent* strength of the stud. If flat sheet metal is placed between the steel/concrete, simulating a specimen with deck without a profile, the stud strength is about 85% of the strength of studs in a solid slab specimen without sheet metal. This decrease in strength is probably due to the reduction of friction at the steel/concrete interface.
3. Increasing the normal load applied to the specimen increases the *apparent* strength of the stud, probably because the frictional resistance increased.
4. The AISC equations give adequate predictions of the strengths of studs in solid slabs when normal load is applied to the specimen. When normal load is not applied, the stud strengths are less than 90% of the AISC predictions.

The composite slab push-out test data resulted in these conclusions:

5. Strong position studs in 2 in. and 3 in. deck exhibited stud shearing failures.
6. Weak position studs in 2 in. and 3 in. deck exhibited rib punching failures, usually before 0.2 in. of slip occurred.
7. Studs placed in 4 1/2 in. or 6 in. deck failed by rib shearing. Rib cracking usually occurred before a load of 10 k was reached. Severe disfigurement of the ribs occurred, along with "bowing" of the slab. Although not calibrated for use with deep decks, the AISC equations underpredicted the strengths of studs in deep decks.

8. The AISC (*Load* 1993) and CSA (*Steel* 1994) strength prediction methods are generally unconservative, especially for weak position studs. The Eurocode 4 (*EN* 2001) strength prediction method is more conservative than the AISC and CSA strength prediction methods. The Johnson and Yuan (1997) method more accurately predicts the strengths of both strong and weak position studs. However, the failure mode must be predicted before the appropriate equations can be used. The equations are also lengthy, making the method impractical.

The bare stud test data resulted in these conclusions:

9. The strength of a bare stud tested in shear, in which a force is applied very close to the base of the stud, is about 70% of the tensile strength.
10. The strength of a bare stud, in which a force is applied 0.5 in. from its base, is about 50% of the tensile strength.

An evaluation of 202 push-out tests leads to the following conclusions:

11. The strength of studs welded through steel deck is primarily a function of the tensile strength, A_sF_u. For strong position single studs in 2 in. and 3 in. deck, the average strength was $0.68A_sF_u$, with a coefficient of correlation of 0.930 and a coefficient of variation of 15.0%. Concrete strength and deck height had no predictable influence on the strength of these studs.
12. The maximum load on the strong position single studs was reached usually before 0.2 in. of slip occurred.

13. For weak position single studs in 2 in. and 3 in. deck, the average strength was 0.48 A_sF_u, with a coefficient of correlation of 0.943 and a coefficient of variation of 17.9%.

14. The maximum load on the weak position single studs occurred around 0.2 in. of slip, which is approximately when rib punching is observed. The load usually dropped or remained the same for several increments of slip. Occasionally, the load increased when very large slips were reached.

15. Because weak position studs usually fail by rib punching, their strength is dependent on the deck thickness. Factors, which are multiplied by the base strength of 0.48 A_sF_u, were developed to account for this influence.

16. "Strong position studs" are defined as those studs that have a concrete cover more than 2.2 in. The cover is measured from the center of the stud's longitudinal axis to the deck rib, at the mid-height of the rib, on the load bearing side of the stud. "Weak position studs" are defined as those studs that have a concrete cover less than 2.2 in.

17. Staggered position studs have an average strength of $0.52A_sF_u$.

18. Based on limited test data, it is recommended that the strength of a stud in a pair be taken as 85% of the strength of a single stud.

19. An equation to account for the reduction in stud strength when $d/t \geq 2.7$ was developed.

These conclusions were based on the results of beam tests:

20. Three new beam tests, along with 61 beam tests performed at VT and elsewhere, were used to verify the accuracy of the proposed stud strength prediction model. The beam strengths were predicted using the AISC (*Load* 1993) flexural model. Stud strengths were predicted using the AISC stud strength prediction equations and also using the new prediction equations.
21. From the three new beam tests, the beam with strong position studs was the strongest with a flexural strength of 412.1 k-ft (88% of the AISC prediction and 97% of the new prediction). The beam with weak position studs had a flexural strength of 379.0 k-ft (81% of the AISC prediction and 97% of the new prediction). The beam with strong position pairs of studs had a capacity of 376.1 k-ft (80% of the AISC prediction and 92% of the new prediction).
22. From the three new beam tests, the strong position studs had back-calculated strengths of 17.7 k per stud (60% of the AISC prediction and 88% of the new prediction). The weak position studs had strengths of 12.8 k (43% of the AISC prediction and 90% of the new prediction). The strong position studs placed in pairs had strengths of 12.4 k (42% of the AISC prediction and 72% of the new prediction). The back-calculated strengths were obtained by determining the stud strength necessary to achieve the experimental flexural strength using the AISC flexural model.

23. An evaluation of all beam tests showed that the new stud strength method results in more conservative predictions for stud strengths, and therefore, for beam strengths, than the AISC (*Load* 1993) method.

24. A resistance factor for composite beam strength, using the AISC flexural model (*Load* 1993), Composite Beam Criteria (Hansell et al 1978), and new stud strength prediction model, was found to be 0.861. This is assuming that the load effects and resistance are statistically independent random variables and are lognormally distributed and is based on all beam test results reported in Chapter 8. Using modified resistance factor calculations that include the reliability of the studs results in a resistance factor of 0.887 if approximations are made in the expression for the flexural strength. If these approximations are not made, and the actual expression for the flexural strength is analyzed, the resistance factor is 0.884.

10.3 Recommendations

1. More research is needed on small (3/8 in.) and large (7/8 in.) diameter studs. The majority of push-out tests and beam tests have been done using 3/4 in. studs.
2. If decks deeper than 3 in. are deemed practical for use, more tests should be done to evaluate the adequacy of the new stud strength model.
3. The new stud strength model accounts for the stud position in the deck rib, which is the most important parameter affecting stud strength. This method can be used in design. A phi-factor of 0.88 should be used for the flexural strength of a composite

beam with deck ribs perpendicular to the beam, if the AISC flexural theory and the new stud strength model are used to calculate the flexural strength.