

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The data and results obtained from 106 pushout tests performed on the Elco Grade 8 standoff screw shear connector are presented in this report, along with the corresponding analysis and discussion of those results. This study is intended to evaluate the performance of the Elco Grade 8, 5/16 in. diameter standoff screw and supplements previous research performed by Hankins (1994) and Lauer (1994) at Virginia Tech.

The pushout tests were performed on standoff screw heights ranging from 2 in. to 3.5 in. The screws were driven into equal-leg double angles designed to simulate the top chord of a typical steel joist. The thicknesses of the base angle members ranged from 0.109 in. to 0.313 in. Several different types of profiled steel deck were used in the tests, and solid slab tests were performed, as well.

Five series of tests were performed on the Elco Grade 8 standoff screw: the preliminary series and series A through D. The results obtained from the preliminary series were used to modify the test series A through D. Each of the four test series, A through D, was distinct in the type of profiled steel deck used. Series A utilized Vulcraft 0.6C deck, series B used Vulcraft 1.0C deck, series C used Vulcraft 1.5C deck, and series D contained 1.5VL deck. The total number of screws used in each test was varied to examine any effects that grouping the standoff screws may induce. Series A, C, and D contained sufficient steel reinforcement to prevent longitudinal splitting, while series B contained only welded wire fabric reinforcement.

Analysis of the data obtained from the pushout tests consisted of comparing the test results from this study to those obtained by Hankins (1994); evaluating the applicability of Hankins' predictive shear strength equation to the test parameters of

series A through D; evaluating the effects of various test parameters on the shear strength of the standoff screw; and examining the effects of grouping the standoff screws in the deck ribs. The effects of rib failure on the shear strength of the standoff screw were also examined, as well as the performance of the standoff screw in solid slab applications. Predictive equations for the shear strength of the Elco Grade 8 standoff screw were developed based on screw-related failure modes, concrete rib failures, and longitudinal splitting of solid slabs.

5.2 Conclusions

Based on the pushout test data and subsequent analysis, the following conclusions can be drawn regarding the performance of the Elco Grade 8 standoff screw:

1. The Elco Grade 8 standoff screw is an effective means of shear connection and is a viable alternative to the conventional welded shear stud in short-span composite joists.
2. The presence of transverse reinforcement greatly increases the shear strength of the Elco Grade 8 standoff screw, both in solid slabs and in concrete slabs formed with profiled steel deck. The purpose of transverse reinforcement is to prevent and/or limit longitudinal splitting in the concrete slabs. But, there appears to be a limit to the beneficial effects of transverse reinforcement, as there is a point where additional reinforcement does not contribute to additional shear strength of the standoff screw.
3. Lapping 1.0C deck in the region of the standoff screws has no significant effect on the shear strength of the standoff screws.
4. Staggering the screws, one per rib, provides no discernable advantage over pairing the screws in every other rib of 1.0C deck.
5. Placing the screws in groups of two or more per rib is detrimental to the ultimate shear strength per screw that can be obtained.
6. Excessive rotation of the screws in very thin base angles, especially 0.109 in. thick base angles, causes the standoff screws to be loaded primarily in tension, leading to the failure mode of screw pullout from the base angles. Thicker base angles limit any

- significant rotation, causing the screws to be loaded more in shear, leading to the most common type of failure observed in this study, screw shear.
7. In general, test specimens with base angles of medium thickness (usually 0.187 in.) can achieve higher ultimate shear loads than those with relatively thin (0.109 in.) or relatively thick (0.250 in.) base angles. This is because a medium base angle thickness is flexible enough to allow for some rotation of the standoff screw, but not overly flexible so as to cause tensile loading of the screw. This combined loading leads to greater ultimate strength of the standoff screws, as opposed to screws loaded primarily in shear or primarily in tension.
 8. The tendency for standoff screws to fail by screw pullout from thin base angles can be reduced if the amount of concrete surrounding the screw is increased. This is evident in looking at the failure modes from series C (1.5C deck). The greater rib area (average rib width \times rib height) in 1.5C deck limited the standoff screw rotation and caused some test specimens with 0.109 in. base angles to fail by screw shear. This did not occur in any other types of deck.
 9. Grouping the screws in 1.5C deck does not reduce the ultimate shear strength of the Elco Grade 8 standoff screw to the extent that it does in the other types of deck examined in this study. This may be a result of the greater rib width of the 1.5C deck.
 10. Grouping the screws increases the likelihood of rib failure in 1.5C and 1.5VL deck. The deck profile of 1.5VL deck makes it especially prone to premature brittle rib failure of the concrete slab, greatly reducing the shear strength of the standoff screws.
 11. An embedment depth of 1.5 in. above the top of the deck profile is sufficient to develop the full shear strength of the Elco Grade 8 standoff screw. Increasing the embedment depth to greater than 1.5 in. does not provide any conclusive gain in shear strength of the standoff screw.
 12. Substantial rotation at the base of the standoff screws causes the top chord angles to deform and leads to the development of a plastic hinge above the upper-most screws. This deformation can lead to top chord buckling of the pushout test specimen.

13. Hankins' proposed shear strength equation (Eq. 1.4) is not applicable to the results obtained in this study for several reasons. First, the standoff screws used in Hankins' study were embedded only 1 in. above the top of the deck profile compared to 1.5 in. in most of the tests contained in this test program. Second, the test series in Hankins' program contained only welded wire fabric as reinforcement, as opposed to series A, C, and D in this study which contained sufficient steel reinforcement to prevent longitudinal splitting of the concrete. Hankins' tests also contained only 8 total screws, significantly less than most of the specimens contained in this test program. These variations in test parameters led to different types of failure modes in the two test programs. The failure modes in Hankins' tests were essentially concrete cone failures, while those from this study were primarily screw-related failures (i.e. screw pullout and screw shear). Thus, while Hankins' equation effectively predicts the shear strength of the Elco Grade 8 standoff screw in cases of concrete cone failure, it is incompatible with the test results presented here. The inapplicability of Hankins' concrete cone model necessitates the development of a new predictive equation based on the screw-related failure observed in this study.
14. The ultimate shear strength of the Elco Grade 8, 5/16 in. diameter standoff screw is inversely related to the ratio of average rib width to rib height, in contrast to the conventional belief that there should be a direct relationship between the two variables. The flexibility and ductility of the Elco Grade 8 standoff screw are important factors influencing the ultimate shear strength of the connector. Just as a flexible base angle can yield greater ultimate shear strength of the standoff screw, a deep, narrow rib is more flexible than a wide, shallow rib and can provide greater ultimate shear strength. This is clear in comparing the results from test groups C1-C3 with D1-D3. The deeper, narrower rib of 1.5VL deck (series D) allowed greater rotation of the standoff screw leading to greater shear strength and higher average slips.
15. Although the high slip values recorded in most tests illustrate the great ductility of the Elco Grade 8 standoff screw, these amounts of slip are impractical for full-scale

- composite joists. At very high values of slip, i.e. in the range of 0.6 to 1.0 in., small increases in shear load can lead to large increases in slip at the steel-concrete interface, causing permanent slippage. Therefore, it is not feasible to consider the ultimate shear strength of the Elco Grade 8 standoff screw in design and the slip at the steel-concrete interface must be limited to prevent permanent deformation.
16. Limiting the slip at the steel-concrete interface to 0.2 in. is practical for design purposes for several reasons. First, 0.2 in. of slip is generally observed to occur just before the onset of nonlinear behavior of the standoff screws. If the ultimate shear load is assumed to occur at 0.2 in. of slip, then the design load for the Elco Grade 8 standoff screw would most likely be well within the elastic region of the Load vs. Slip plot, limiting any excessive slippage and permanent deformation. Also, the maximum shear load for a typical welded shear stud occurs at approximately 0.2 in. of slip (TRW Nelson 1977). To obtain similar behavior from the standoff screw as that obtained from welded shear studs, the maximum shear load should likewise be assumed to occur at 0.2 in. of slip.
 17. Two parameters have the most significant influence on the shear strength of the Elco Grade 8 standoff screw at low values of slip (0.2 in.): top chord thickness and rib area. The shear strength of the standoff screw is directly related to each of these variables. The effects of these parameters on the shear strength at low slips are in contrast to the same effects on the ultimate shear strength of the standoff screw. This is because thicker top chord angles and greater rib area provide greater stiffness and less screw rotation, leading to greater shear strength at low values of slip. Thus, although less screw rotation may cause the standoff screws to fail at lower ultimate shear loads, this behavior leads to lower slip values corresponding to higher shear loads at 0.2 in. of slip. In other words, the elastic portion of the Load vs. Slip plot is steeper for tests with thicker base angles and greater rib area.
 18. The effect of grouping the screws is minimal at low slips, with the exception of groups of four screws or more in 1.5VL deck.

19. Through a multiple linear regression, an equation has been developed to accurately predict the shear strength of the Elco Grade 8 standoff screw at 0.2 in. of slip as a function of concrete compressive strength, top chord thickness, and rib area. This equation is based on screw-related failures and is applicable to the test data from series A and C and test groups D1-D6. The lack of sufficient steel reinforcement in series B to prevent longitudinal splitting causes this equation to overestimate the shear strength of the Elco Grade 8 standoff screw in those tests. Test groups D7-D12 failed prematurely by brittle rib failure. The final form of the equation is shown below:

$$V_s = \sqrt{f'_c} (0.034 + 0.0012A_r + 0.068t_{TC}) \quad (4.3)$$

where:

V_s = shear strength per screw, kips

f'_c = concrete compressive strength, psi

A_r = rib area, in.²

= average rib width × nominal rib height

t_{TC} = top chord thickness, in.

This equation is only applicable to the 5/16 in. diameter Elco Grade 8 standoff screw when the screw is embedded at least 1.5 in. above the top of the deck profile. It can only be used for the following cases:

- 0.6C deck, no more than one screw per rib
- 1.0C deck, no more than two screws per rib
- 1.5C deck, no more than four screws per rib
- 1.5VL deck, no more than two screws per rib

20. Slabs formed with Vulcraft 1.5VL deck are prone to premature, brittle rib failures when four or more standoff screws are placed in each rib. These concrete-related failures observed in test groups D7-D12 can not be predicted by Eq. 4.3. Hankins' (1994) equation (Eq. 1.4) can be modified to estimate the rib failure load per deck rib for test specimens with 1.5VL deck. The term representing the wedge-shaped concrete cone failure surface in Hankins' original equation can be replaced by

Lloyd and Wright's representation of the rib shear failure surface area. This equation, shown below, can not be used to accurately predict rib shear failure strengths in other types of deck.

$$V_{rs} = 0.11\sqrt{A_{rs}\sqrt{f'_c}} \quad (4.4)$$

where:

V_{rs} = rib shear strength, kips

A_{rs} = rib shear failure surface area, in.² (Lloyd and Wright 1990)

$$= w_{r2}\sqrt{\frac{b^2}{4} + (H_s - h_r)^2} + b\sqrt{\frac{w_{r2}^2}{4} + (H_s - h_r)^2}$$

b = width of concrete rib, in.

h_r = nominal rib height of steel deck, in.

H_s = height of shear connector, in.

w_{r2} = concrete rib width at top flange of steel deck, in.

f'_c = concrete compressive strength, psi

This equation is only valid for specimens containing 1.5VL deck and more than 2 standoff screws per rib. The screws must be 5/16 in. in diameter. This equation may not be used in practice since there is no method to accurately determine the width of the failure surface. The predicted total rib shear failure load can be divided by the predicted shear strength per screw as calculated by Eq. 4.3 to estimate the maximum number of standoff screws per rib that can be used before rib shear failure becomes a viable failure mode.

21. Most of the rib failures observed in 1.5VL deck were very brittle with less than 0.2 in. of slip at the steel-concrete interface before failure. Therefore, these types of failures must be avoided.
22. For the solid slab configurations examined in this study, the following equation can be used to accurately predict the shear strength of the Elco Grade 8 standoff screw in solid slabs (*Commentary on* 1990):

$$v_r = 0.03\eta f_{cu} A_{cv} + 0.7A_{sv} f_y \leq 0.8\eta A_{cv} \sqrt{f_{cu}} \quad (4.5)$$

where:

v_r = shear resistance per unit length of each shear plane (kips/in.)

η = 1.0 for normal weight concrete and 0.8 for lightweight concrete

f_{cu} = cube strength of concrete (ksi)

$$\approx 1.25 f'_c$$

A_{cv} = cross-sectional area of concrete per unit length of any shear plane (in.²/in.)

A_{sv} = amount of steel reinforcement crossing each shear plane (in.²/in.)

f_y = yield strength of steel reinforcement (ksi)

This equation is based on longitudinal splitting of the concrete slab. The shear resistance per unit length must be multiplied by the length of the slab and the number of shear planes to determine the total shear resistance of the test specimen. Equation 4.5 is only valid for 3 in. thick solid slab specimens with 5/16 in. diameter Elco Grade 8 screws with a standoff length of 2.5 in. The screws must be spaced no more than 3.75 in. apart. If the screws are spaced too far apart to induce longitudinal splitting to some extent, then Eq. 4.5 is not valid.

5.3 Limitations

The data and results obtained in this study apply only to the 5/16 in. diameter Elco Grade 8 standoff screw. The conclusions drawn from the analysis of this data can not be applied to other types of shear connectors without sufficient research to support such findings. In addition, the predictive equations presented in this report are only compatible with the deck types and configurations used in this research program. The screw heights applicable to these equations are 1.5 in.-2.0 in. above the top of the deck profile. Longer or shorter screws may lead to failure modes that are not investigated here. Specimens containing larger groups of screws per deck rib than those tested in this study are also incompatible with the predictive equations, as different failure modes may result.

5.4 Suggestions and Recommendations for Further Research

Based on the observations and findings obtained from the research program, as well as the conclusions drawn regarding the shear strength of the Elco Grade 8 standoff screw, the following suggestions and recommendations are made:

1. Full-scale tests must be performed to evaluate the compatibility of the corresponding pushout test series and to assess the accuracy of the predictive equations presented in this report. Particular attention should be paid to the failure modes observed in this program in comparison to those in full-scale tests.
2. The effects of transverse reinforcement on the shear strength of the Elco Grade 8 standoff screw should also be examined in the full-scale tests. In particular, comparisons should be made regarding the amount of transverse reinforcement used in the pushout tests to prevent longitudinal splitting compared to the amount used in full-scale tests and its effect on longitudinal splitting. In addition, the lateral restraint provided by the greater width of concrete surrounding the standoff screws in full-scale applications must be assessed for both interior and edge joists.
3. Additional pushout tests should be performed to evaluate the performance of the Elco Grade 8 standoff screw in other types of deck commonly used in composite joist construction. The data compiled from additional pushout tests can be used to check the validity of the predictive equations presented in this report.
4. Pushout tests should be performed on 2.5 in. standoff screws in 1.0C deck reinforced with steel reinforcing bars to prevent longitudinal splitting. The lack of reinforcement in the 1.0C deck tests limited the applicability of the Eq. 4.3 to the test configurations of series B. The standoff length of 2.5 in. is recommended because an embedment depth of 1.5 in. above the top of the deck profile is sufficient to develop the full shear strength of the standoff screw. The results of these tests containing sufficient reinforcement can be compared with the predicted values to further evaluate the accuracy of Eq. 4.3.

5. The standoff screw heights in future pushout tests must be at least 1.5 in. above the top of the deck profile to fully develop the shear strength of the Elco Grade 8 standoff screw.
6. Future top chord sections used in pushout test specimens should contain a 1 in. plate as opposed to the 0.5 in. plate used in most of the tests in this study. A 1 in. plate will greatly reduce the likelihood of top chord buckling and provides a more stable surface on which to place a loading plate.
7. The leg length of top chord double angles should be at least 1.5 in. There were instances in this research where the small leg length of 1.25 in. double angles led to the standoff screw being erroneously placed in the outer edge of the leg, and not fully embedded in the leg.
8. Screws should not be placed in groups of more than four per rib in 1.5C deck and two per rib in 1.5VL deck to reduce the risk of premature rib failure.
9. Attention should be given to the method of attaching the screws to the top chord sections. The current use of an electric screw gun is time consuming and laborious.