CHAPTER 4
ANALYSIS AND INTERPRETATIONS

4.1 General

This chapter deals with the analysis of the data collected from the 106 pushout tests performed for this study and the interpretations of those results. The strength of the standoff screw will first be examined in cases in which there is no more than one screw per rib. Hankins' (1994) equation for predicting the shear strength of the Elco Grade 8 standoff screw will be evaluated by comparing predicted results to the experimental screw shear results obtained in this study. Hankins' equation will be modified if necessary, or a new predictive equation will be proposed to better reflect the behavior of the standoff screws observed in this study. The effects of base angle thickness and deck profile will be examined. Once the shear strength of single standoff screws has been examined, the effects of grouping the screws in the deck ribs will be analyzed.

The results obtained from the preliminary series were used to examine the effects of transverse reinforcement and to determine the amount of transverse reinforcement to be used in the remaining series of tests. Therefore, the results obtained from the preliminary test series will not be analyzed except for a discussion of the ultimate strength of the standoff screws in solid slabs (test groups P7-P10).

4.2 Ultimate Shear Strength of Standoff Screws in Profiled Steel Deck

This section will examine the shear strength of the Elco Grade 8, 5/16 in. diameter standoff screw in concrete slabs formed with profiled steel deck. Only those tests with one screw per rib will be analyzed in this section. In addition, only the results obtained from tests having screws embedded 1.5 in. above the top of the deck profile will be examined. It is believed that 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. Also, the only series in which multiple screw heights were effectively examined was series B. It is clear in looking at Figure 4.1 that increasing the embedment depth to greater than 1.5 in. above the top of the deck has little effect on the ultimate strength of the standoff screws.

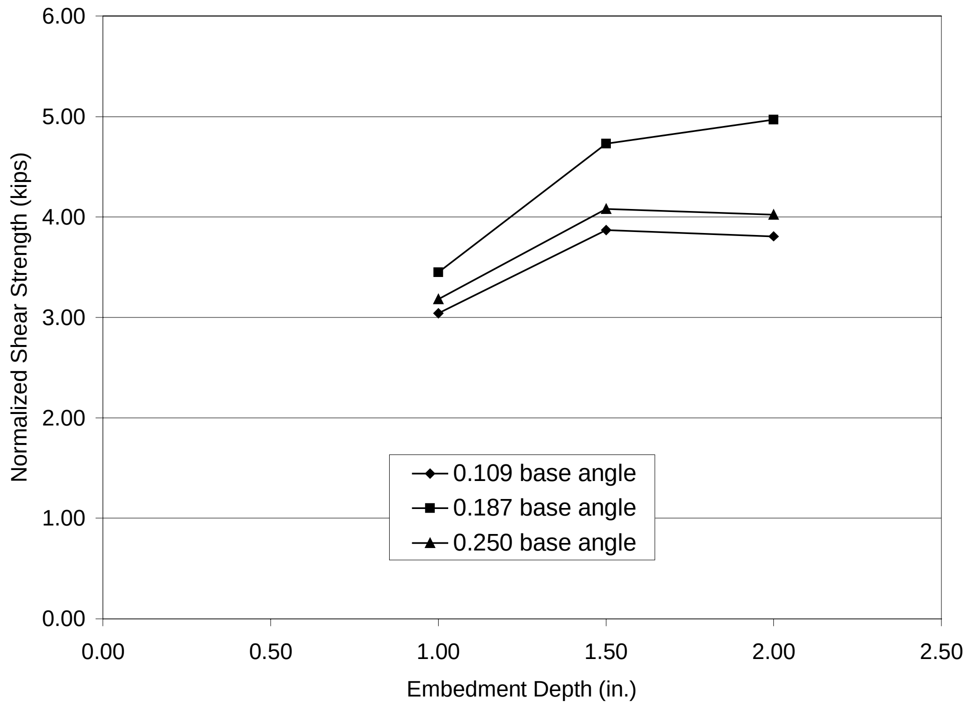

Figure 4.1 Average Normalized Shear Strength per Screw vs. Embedment Depth Above Top of Deck (Series B)

Test groups A1 and A2 will not be included in this analysis because these test groups contained one screw in every other rib, as opposed to one screw in each rib. In summary, the tests to be analyzed will be A6-A8, B4-B6, C1-C3, and D1-D3, shown in Table 4.1. As can be seen in the table, these specimens have the same embedment depth with respect to the deck (1.5 in.), the same number of screws per rib (1), and the same three base angle thicknesses (0.109 in., 0.187 in., and 0.250 in.).

Table 4.1 Results of Tests with One Screw Per Rib

Test Number	Deck Type	Slab Depth (in.)	Screw Height (in.)	Number of Screws/Rib	Top Chord Thickness (in.)	Concrete f'c (psi)	Peak Shear Load/Screw (kips)	Normalized Peak Shear Load/Screw (kips)	Failure Mode
A6-1	0.6C	2.25	2	1	0.109	5080	4.12	3.66	screw pullout
A6-2	0.6C	2.25	2	1	0.109	5080	4.12	3.66	screw pullout
A7-1	0.6C	2.25	2	1	0.187	5080	5.18	4.60	screw shear
A7-2	0.6C	2.25	2	1	0.187	5080	5.41	4.80	screw shear
A8-1	0.6C	2.25	2	1	0.250	5080	5.06	4.49	screw shear
A8-2	0.6C	2.25	2	1	0.250	5080	5.22	4.63	screw shear
B4-1	1.0C	2.75	2.5	1	0.109	3780	3.61	3.71	screw pullout
B4-2	1.0C	2.75	2.5	1	0.109	3780	3.91	4.02	screw pullout
B5-1	1.0C	2.75	2.5	1	0.187	3780	4.61	4.74	screw shear
B5-2	1.0C	2.75	2.5	1	0.187	3780	4.59	4.72	screw shear
B6-1	1.0C	2.75	2.5	1	0.250	3780	4.00	4.11	screw shear
B6-2	1.0C	2.75	2.5	1	0.250	3780	3.93	4.04	screw shear
C1-1	1.5C	3.25	3	1	0.109	5756	4.05	3.38	screw shear
C1-2	1.5C	3.25	3	1	0.109	5756	4.04	3.37	screw shear
C2-1	1.5C	3.25	3	1	0.187	5756	5.16	4.30	screw shear
C2-2	1.5C	3.25	3	1	0.187	5756	5.36	4.47	screw shear
C3-1	1.5C	3.25	3	1	0.250	4310	4.70	4.53	screw shear
C3-2	1.5C	3.25	3	1	0.250	4310	4.11	3.96	screw shear
D1-1	1.5VL	3.25	3	1	0.109	3568	4.09	4.33	screw pullout
D1-2	1.5VL	3.25	3	1	0.109	3568	3.88	4.11	screw pullout
D2-1	1.5VL	3.25	3	1	0.187	3568	5.80	6.14	screw shear
D2-2	1.5VL	3.25	3	1	0.187	3568	5.51	5.83	screw shear
D3-1	1.5VL	3.25	3	1	0.250	3568	4.72	5.00	screw shear
D3-2	1.5VL	3.25	3	1	0.250	3568	5.62	5.95	screw shear

4.2.1 Hankins' Proposed Shear Strength Equation

The only predictive equation for the strength of the Elco Grade 8 standoff screw that currently exists is that of Hankins (1994). As discussed in Section 1.2, Hankins performed 65 pushout tests on the Elco Grade 8 standoff screw in concrete slabs formed with various deck profiles. Through an analysis of the pushout test data, the following equation, based on a wedge shaped concrete cone failure surface, was proposed to predict the shear strength per screw:

$$V_{wc} = 0.11\sqrt{A_{wc}\sqrt{f'_c}} \qquad (1.4)$$

where:

V_{wc} = connector strength, kips

A_{wc} = surface area of wedge shaped tensile concrete pullout cone, in.^{2}

$$= 2w_{r2}\sqrt{\frac{w_{r2}^2}{4} + \left(H_s - h_r\right)^2} + w_{r2}\sqrt{w_{r2}^2 + 2\left(H_s - h_r\right)^2} + 2w_{r1}\sqrt{3h_r^2}$$

f'_c = concrete compressive strength, psi

h_r = nominal rib height of steel deck, in.

H_s = total length of shear connector, in.

w_{r1} = concrete rib width at bottom of flange of steel deck, in.

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

This equation was applied to the test parameters and data compiled from the tests listed in Table 4.1. Comparisons between the predictive values obtained from the equation described above and the average experimental values obtained from the pushout tests are shown in Table 4.2.

Table 4.2 Comparison of Hankins' Proposed Shear Strength Equation and Average Experimental Results

Test Group	Deck Type	Slab Depth (in.)	Screw Height (in.)	Screws Per Rib	Top Chord Thickness (in.)	Concrete f'c (psi)	Peak Shear Load/Screw (kips)	V_{wc} (kips)	$\frac{V\ experimental}{V\ predicted}$
A6	0.6C	2.25	2.0	1	0.109	5080	4.12	3.22	1.28
A7	0.6C	2.25	2.0	1	0.187	5080	5.30	3.22	1.64
A8	0.6C	2.25	2.0	1	0.250	5080	5.14	3.22	1.59
B4	1.0C	2.75	2.5	1	0.109	3780	3.76	4.33	0.87
B5	1.0C	2.75	2.5	1	0.187	3780	4.60	4.33	1.06
B6	1.0C	2.75	2.5	1	0.250	3780	3.97	4.33	0.91
C1	1.5C	3.25	3.0	1	0.109	5756	4.04	7.45	0.54
C2	1.5C	3.25	3.0	1	0.187	5756	5.26	7.45	0.71
C3	1.5C	3.25	3.0	1	0.250	4310	4.40	6.93	0.64
D1	1.5VL	3.25	3.0	1	0.109	3568	3.99	4.42	0.90
D2	1.5VL	3.25	3.0	1	0.187	3568	5.66	4.42	1.28
D3	1.5VL	3.25	3.0	1	0.250	3568	5.17	4.42	1.17

As is evident from Table 4.2, there is not a good correlation between the predicted values and the experimental test results, mainly due to significant differences in test parameters between Hankins' tests and those performed for this study. First, the screws in Hankins tests were embedded only 1 in. above the top of the deck. As mentioned earlier, the screws used in this test program were generally embedded 1.5 in. above the top of the deck. Second, the slabs in Hankins tests were reinforced with only welded wire fabric, while series A, C, and D in this study contained steel reinforcing bars to prevent longitudinal splitting. In addition, the welded wire fabric that Hankins used was consistently thinner than that used here. Hankins also used only eight screws in each test specimen (four screws each half), while each test in this test program contained at least 10 screws, often significantly more.

These variations in test parameters led to different failure modes in Hankins' tests compared to those observed in this study. The failure modes encountered in Hankins' tests were primarily concrete cone failures, while those from this study were usually screw-related failures. Therefore, while Hankins' model may effectively predict the shear strength of the standoff screw in cases of concrete cone failure, it is inapplicable to the test results contained herein. The closest correlation between the predicted values and experimental results was in the tests from series B. This is most likely due to the fact that series B specimens contained only welded wire fabric as reinforcement in the concrete slabs, while series A, C, and D contained reinforcing bars. As mentioned earlier, Hankins' tests also contained only welded wire fabric reinforcement.

The inapplicability of Hankins' concrete cone model necessitates the development of a new predictive equation for the shear strength of the Elco Grade 8 standoff screw, based on the screw-related failures observed in this study.

4.2.2 Effects of Individual Test Parameters on Ultimate Shear Strength

The first step in the development of a new predictive equation was to examine the effects of individual test parameters on the pushout test results. The two main parameters that were investigated were base angle thickness and deck geometry. The effects of these parameters on the test results were deduced from several plots of the different parameters against the normalized ultimate shear strength per standoff screw obtained from the pushout tests. Through a regression analysis, a curve or line was fit to the data to show the relationship between the test parameter and standoff screw shear strength.

The results from series B will not be considered in the subsequent analyses because of the lack of steel reinforcing bars in those specimens. This lack of reinforcement led to comparatively lower shear strengths for the standoff screws in comparison to series A, C, and D, which did contain reinforcement. These decreased shear strengths were not consistent with most of the trends observed in the analyses.

Omitting the series B results usually led to better fitting curves and more conclusive relationships between shear strength of the standoff screws and the various test parameters. As of May 1998, research is underway to investigate the shear strength of the Elco Grade 8 standoff screw in concrete slabs formed with Vulcraft 1.0C deck (which was used in series B) and reinforced with sufficient steel reinforcement to prevent longitudinal splitting.

4.2.2.1 Effects of Base Angle Thickness

The effects of varying top chord thickness were examined first. The three sizes of top chord double angles that were examined in series A, C, and D were 0.109 in., 0.187 in. and 0.250 in. The relationship between top chord thickness and normalized ultimate standoff screw shear strength is shown in Figure 4.2.

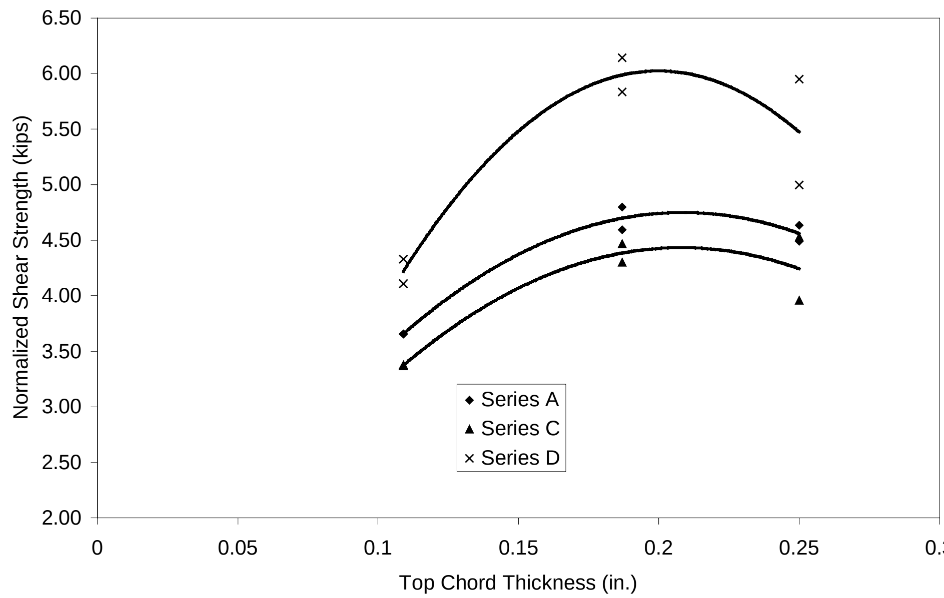

Figure 4.2 Normalized Shear Strength Per Screw vs. Top Chord Thickness

It is clear from Figure 4.2 that the 0.187 in. base angles yielded the greatest shear strength per screw. The 0.109 in. base angles yielded the lowest shear strength per screw. Excessive rotation of the screws in the 0.109 in. base angles caused the standoff screws to be loaded primarily in tension, rather than shear. This observation is supported by the fact that all but two tests in which 0.109 in. base angles were used failed by screw pullout from the base angles (see Table 4.1). The standoff screws that were placed in 0.250 in. base angles experienced less rotation and thus, were loaded primarily in shear. All tests with top chords of 0.250 in. thick double angles failed by screw shear. The 0.187 in. base angles were flexible enough to allow some rotation, but not overly flexible as to cause the standoff screws to be loaded primarily in tension. This balance of shear and tensile loading enabled the screws placed in 0.187 in. base angles to reach higher peak shear loads than those placed in thicker or thinner top chord sections.

The behavior of the standoff screws observed in this study is similar to that of bolts subjected to combined tension and shear. Tests were conducted at the University of Illinois to investigate the strength and behavior characteristics of high-strength bolts subjected to various combinations of tension and shear. Based on the test results, an elliptical interaction curve was developed to represent the behavior of high-strength bolts under combined tension and shear (Kulak, et al 1987). This curve is shown in Figure 4.3. The ultimate strength of a bolt can be represented by a vector from the origin to a particular point on the curve. It is clear in looking at the curve and the corresponding equation that the ultimate strength of high-strength bolts is greater when loaded fully in tension as opposed to being loaded fully in shear. It is also evident that the ultimate strength of a bolt loaded in combined tension and shear, while less than that of a bolt loaded primarily in tension, is greater than that of a bolt loaded primarily in shear. This supports the conclusions drawn earlier about the behavior of standoff screws loaded in combined shear and tension.

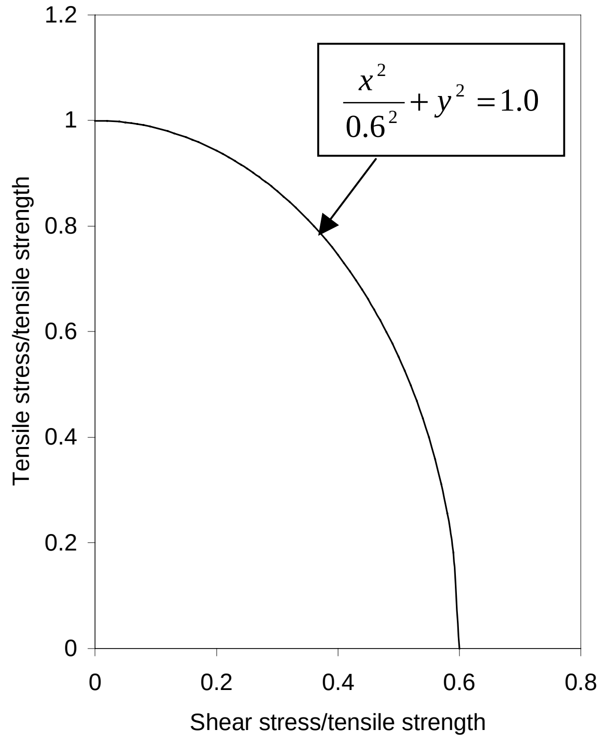

Figure 4.3 Interaction Curve for High-strength Bolts
Under Combined Tension and Shear (Kulak, et al 1987)

4.2.2.2 Effects of Deck Geometry

The effects of the different deck geometries on the ultimate shear strength of the Elco Grade 8 standoff screw are discussed in this section. The effects of deck geometry were examined by plotting the normalized ultimate standoff screw shear strength against the following deck dimensions and ratios: rib width at bottom flange of deck, rib width at top flange of deck, average rib width divided by rib height, and average rib width multiplied by rib height (rib area). The dimensions of the various deck types used in this study are given in Figure 2.4.

The effects of the rib width at the bottom deck flange and at the top deck flange are shown in Figures 4.4 and 4.5, respectively. In both cases, a parabolic relationship can be inferred. Relatively wide (1.5C) or narrow rib widths (0.6C) yielded the lowest shear strengths per screw. These correspond to series C and A respectively. Series D (1.5VL deck) yielded the highest screw strengths.

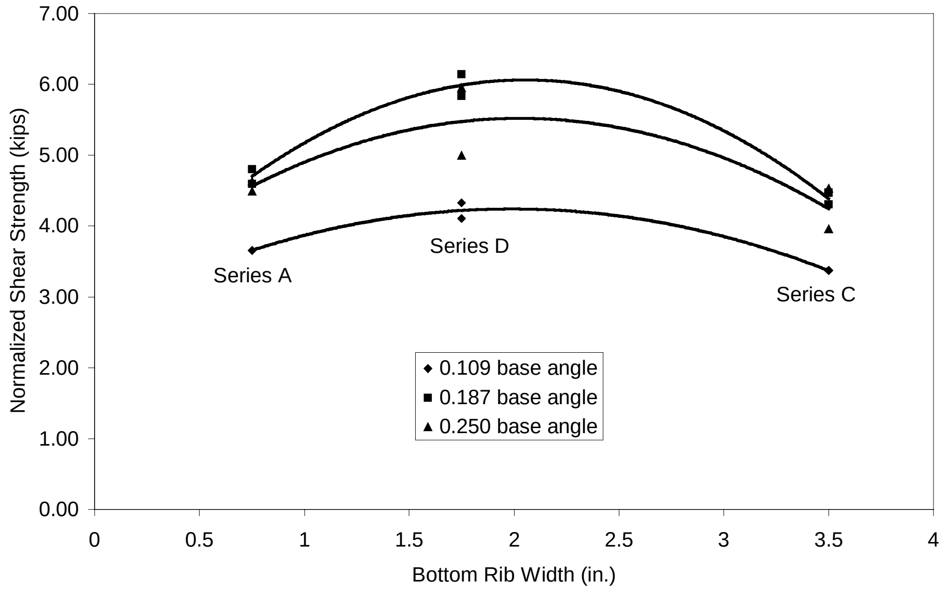

Figure 4.4 Normalized Shear Strength Per Screw vs. Bottom Rib Width

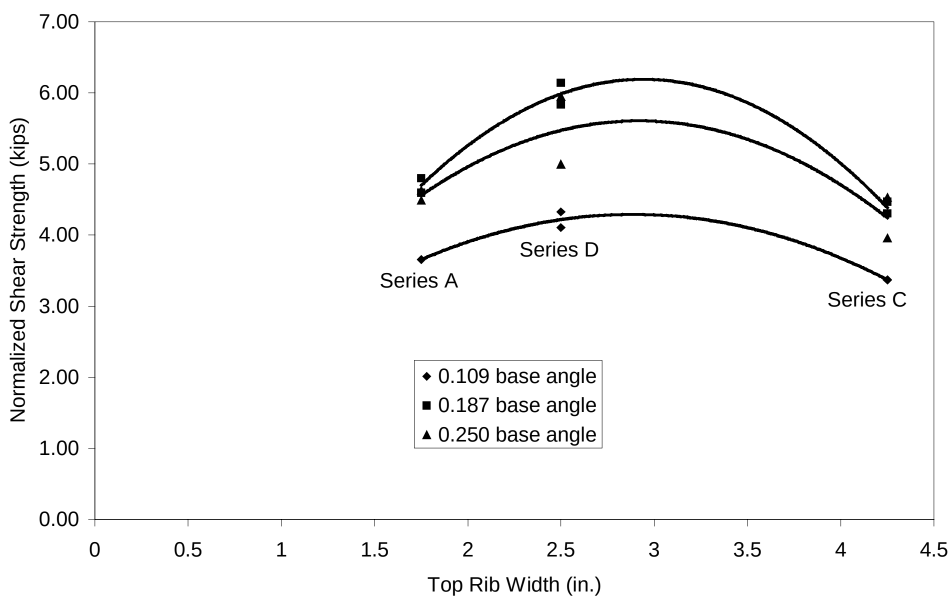

Figure 4.5 Normalized Shear Strength Per Screw vs. Top Rib Width

The height of the particular deck ribs was taken into consideration in the next two plots. Figure 4.6 contains the plot of normalized ultimate screw shear strength versus the area of concrete contained in one deck rib, or rib area. The same conclusions can be drawn from this plot as were drawn from the plots comparing top and bottom rib width to the standoff screw shear strength. Series D yielded the highest screw shear strength values, while series A and C yielded somewhat lower values. Although this plot does show an interesting trend, it does not take into account the ratio of rib width to rib height, i.e. two types of deck could have similar rib areas even though the deck profiles are different. It is difficult to make any definitive conclusions from the parabolic relationship present in Figure 4.6.

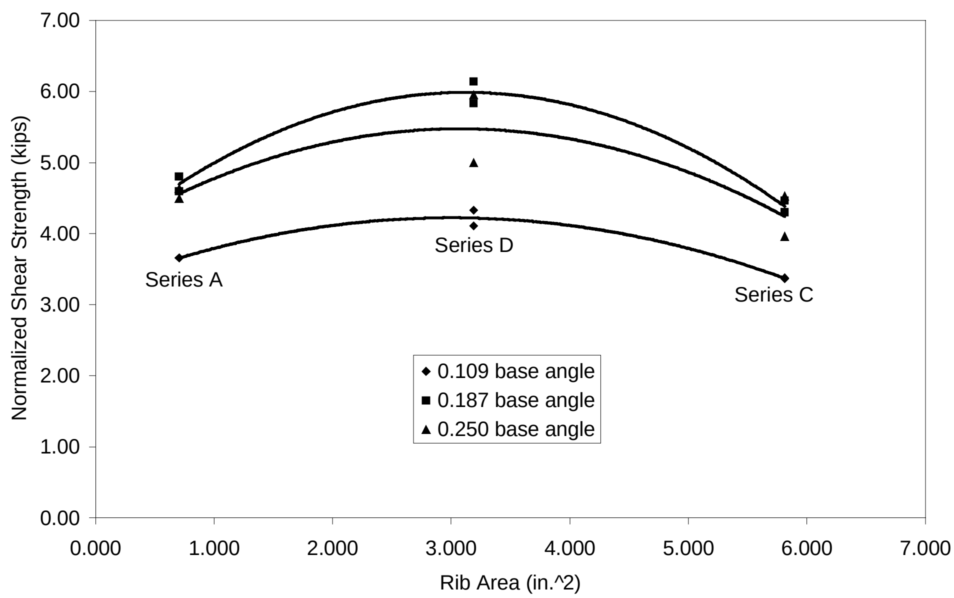

Figure 4.6 Normalized Shear Strength Per Screw vs. Rib Area

The shear strength of standoff screws is plotted against the average rib width to rib height ratio in Figure 4.7, revealing an interesting relationship. This plot shows that a smaller rib width to rib height ratio yields consistently greater shear strength of the standoff screws. This would seem to contradict the conventional belief that a wider, shallower deck rib would yield greater screw strength than a deeper, narrower rib.

However, the ultimate shear strength of the Elco Grade 8 standoff screw is very much dependent on its flexibility and ability to rotate. This is evident in looking at the relationship between shear strength and top chord thickness. The 0.187 in. base angle allowed more rotation than did the 0.250 in. base angle, leading to greater shear strength per screw. Likewise, a deep, narrow rib is more flexible and allows more rotation than a shallow, wide rib. Take, for example, series C and series D. Both series utilized deck with a height of 1.5 in. The average rib width for series C is 3.875 in., while for series D it is 2.125 in. In looking at the Load vs. Slip plots in the data packs for test groups C1-C3 and D1-D3 (Alander, et al 1998b), it is clear that the elastic region of the curves is generally greater for the series C tests. However, the greater rotation allowed by the 1.5VL deck (series D) enabled the standoff screws to reach higher peak shear loads in the inelastic region. This increased screw rotation is supported by the fact that the average slip at the peak shear load for test groups D1-D3 is consistently greater than the slips for test groups C1-C3. The screws in the 1.5C deck (series C) are loaded more in shear, while those in the 1.5VL deck (series D) have a more balanced loading between shear and tension.

Although the high slip values recorded during testing illustrate the great ductility of the Elco Grade 8 standoff screw, these amounts of slip at the steel-concrete interface are impractical for full-scale composite joists. At very large slips, i.e. in the range of 0.6 in. to 1.0 in., small increases in shear load often lead to large increases in slip at the steel-concrete interface, causing significant permanent slippage. Therefore, it is not feasible to consider the ultimate shear strength of the Elco Grade 8 standoff screw in design.

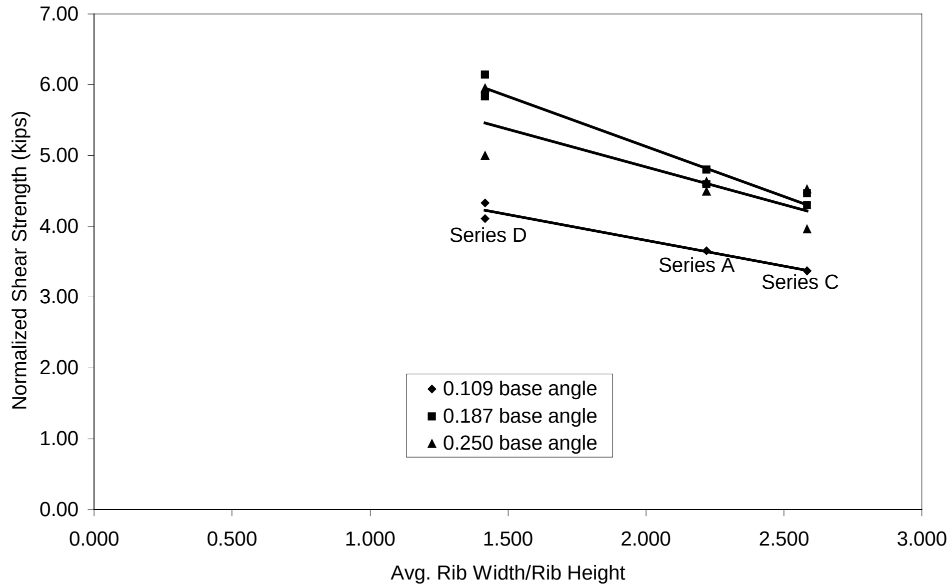

Figure 4.7 Normalized Shear Strength Per Screw vs. Average Rib Width to Rib Height Ratio

4.3 Shear Strength of Standoff Screws at Low Slippage in Profiled Steel Deck

The same parameters that were examined in Section 4.2.2 against ultimate normalized shear strength will be examined in this section against normalized shear strength at 0.2 in. of slip. For the reasons mentioned above, the slip at the steel-concrete interface must be limited for the purposes of design. The slip of 0.2 in. was arbitrarily chosen for a few 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 was assumed to occur at 0.2 in. of slip, then the design load for the Elco Grade 8 standoff screw would certainly be in the elastic region of the Load vs. Slip plot. A load increase of 10 to 20 percent above the design load would still be in the elastic region, without any significant deformation resulting from large amounts of slip (Samuelson 1997). 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.

4.3.1 Effects of Individual Test Parameters on Shear Strength at Low Slippage

The parameters of top chord thickness and deck geometry will be considered in this section, and several plots will be used to show the relationships between these parameters and the normalized shear strength of the Elco Grade 8 standoff screw at 0.2 in. of slip. The shear load values at 0.2 in. of slip were averaged from the eight shear load readings at 0.2 in. of slip on the Load vs. Slip plots in the Data Report. These values are shown in Table 4.3 along with the peak shear loads for comparison. As before, the results from series B will not be included in this analysis.

Table 4.3 Shear Strength Per Screw at 0.2 in. of Slip
For Tests with One Screw Per Rib

Test Number	Deck Type	Slab Depth (in.)	Screw Height (in.)	Number of Screws Per Rib	Top Chord Thickness (in.)	Concrete f'c (psi)	Peak Shear Load Per Screw (kips)	Normalized Peak Shear Load Per Screw (kips)	Shear Load Per Screw at 0.2" Slip (kips)	Normalized Shear Load Per Screw at 0.2" Slip (kips)	Failure Mode
A6-1	0.6C	2.25	2	1	0.109	5080	4.12	3.66	2.71	2.40	screw pullout
A6-2	0.6C	2.25	2	1	0.109	5080	4.12	3.66	2.85	2.53	screw pullout
A7-1	0.6C	2.25	2	1	0.187	5080	5.18	4.60	3.29	2.92	screw shear
A7-2	0.6C	2.25	2	1	0.187	5080	5.41	4.80	3.52	3.13	screw shear
A8-1	0.6C	2.25	2	1	0.250	5080	5.06	4.49	3.96	3.51	screw shear
A8-2	0.6C	2.25	2	1	0.250	5080	5.22	4.63	3.85	3.41	screw shear
B4-1	1.0C	2.75	2.5	1	0.109	3780	3.61	3.71	2.47	2.54	screw pullout
B4-2	1.0C	2.75	2.5	1	0.109	3780	3.91	4.02	2.37	2.44	screw pullout
B5-1	1.0C	2.75	2.5	1	0.187	3780	4.61	4.74	2.62	2.70	screw shear
B5-2	1.0C	2.75	2.5	1	0.187	3780	4.59	4.72	2.97	3.05	screw shear
B6-1	1.0C	2.75	2.5	1	0.250	3780	4.00	4.11	3.23	3.32	screw shear
B6-2	1.0C	2.75	2.5	1	0.250	3780	3.93	4.04	3.13	3.22	screw shear
C1-1	1.5C	3.25	3	1	0.109	5756	4.05	3.38	3.42*	2.85*	screw shear
C1-2	1.5C	3.25	3	1	0.109	5756	4.04	3.37	3.48*	2.90*	screw shear
C2-1	1.5C	3.25	3	1	0.187	5756	5.16	4.30	4.14	3.45	screw shear
C2-2	1.5C	3.25	3	1	0.187	5756	5.36	4.47	4.25	3.55	screw shear
C3-1	1.5C	3.25	3	1	0.250	4310	4.70	4.53	4.24	4.08	screw shear
C3-2	1.5C	3.25	3	1	0.250	4310	4.11	3.96	3.86	3.72	screw shear
D1-1	1.5VL	3.25	3	1	0.109	3568	4.09	4.33	2.92	3.09	screw pullout
D1-2	1.5VL	3.25	3	1	0.109	3568	3.88	4.11	2.70	2.86	screw pullout
D2-1	1.5VL	3.25	3	1	0.187	3568	5.80	6.14	3.25	3.44	screw shear
D2-2	1.5VL	3.25	3	1	0.187	3568	5.51	5.83	3.10	3.28	screw shear
D3-1	1.5VL	3.25	3	1	0.250	3568	4.72	5.00	3.34	3.54	screw shear
D3-2	1.5VL	3.25	3	1	0.250	3568	5.62	5.95	3.29	3.49	screw shear

* peak shear load occurred before 0.2 in. of slip

4.3.1.1 Effects of Base Angle Thickness

The effects of varying top chord thickness on the shear strength at 0.2 in. of slip are shown in Figure 4.8. Instead of a parabolic relationship, as before, there is now clearly a linear relationship. The thicker the base angle, the greater the shear strength at

0.2 in. of slip. In this case, less screw rotation, and thus less slip, results in greater shear strength for the standoff screws. The more rigid base of thicker top chord angles limits the rotation of the screw and increases the shear load in the initial portion of the pushout test. Thus, although the limited screw rotation in thicker base angles may cause the standoff screws to fail at lower shear loads, this behavior leads to lower slip values and relatively higher shear loads early in the testing procedure. In other words, the elastic portion of the Load vs. Slip plot is steeper for tests with thicker base angles, indicating greater stiffness.

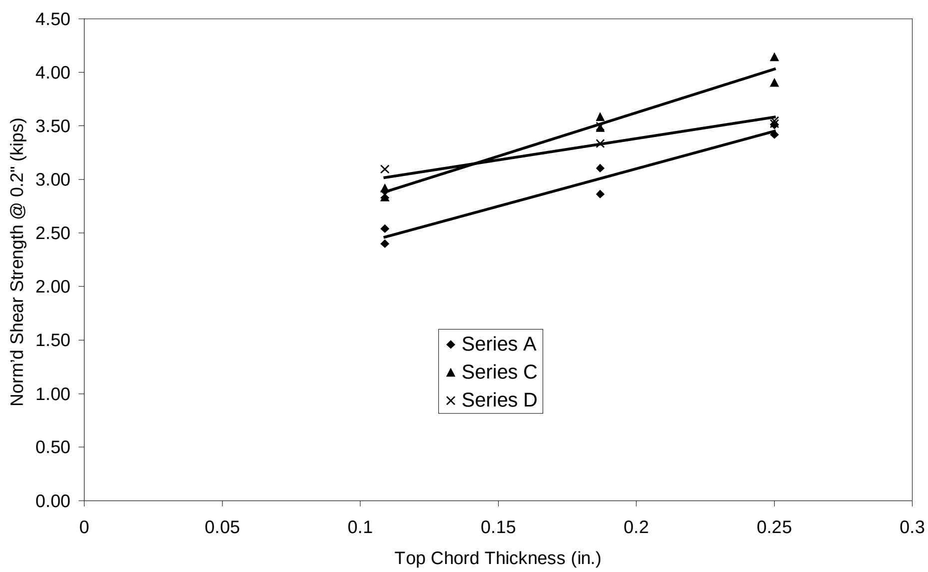

Figure 4.8 Normalized Shear Strength Per Screw at 0.2 in. Slip vs. Top Chord Thickness

4.3.1.2 Effects of Deck Geometry

The effects of several deck dimensions and ratios on the shear strength of the Elco Grade 8 standoff screw at 0.2 in. of slip are presented in this section. These are the same variables that were examined in Section 4.2.2.2 versus the ultimate shear strength of the Elco Grade 8 standoff screw.

The standoff screw shear strength at 0.2 in. is plotted against the rib width at the bottom deck flange and at the top deck flange in Figures 4.9 and 4.10, respectively.

Linear relationships can be inferred from the data plotted in Figure 4.9, although the trend of the data for the 0.109 in. base angle is more parabolic. It can be seen that a wider rib width at the bottom flange of the deck yields higher shear strength values at 0.2 in. of slip, especially for the thicker base angles of 0.187 in. and 0.250 in. Thus, a wider concrete rib is stiffer than a narrow rib, resulting in a steeper elastic region on the Load vs. Slip plots. As before, this greater stiffness at the initial stages of loading leads to greater shear strength at low slips, i.e. approximately 0.2 in. The plot in Figure 4.10 provides less conclusive information. There does not seem to be a consistent relationship between the standoff screw shear strength at 0.2 in. of slip and the rib width at the top deck flange. This suggests that the amount of concrete around the base of the standoff shank is more influential on the shear strength of the standoff screw than the amount of concrete surrounding the upper portion of the standoff shank.

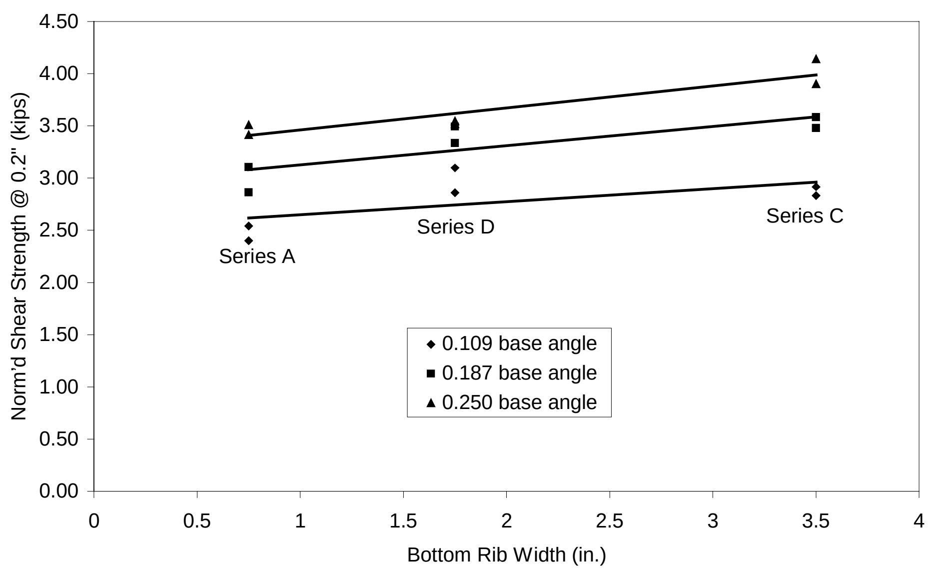

Figure 4.9 Normalized Shear Strength Per Screw at 0.2 in. Slip vs. Bottom Rib Width

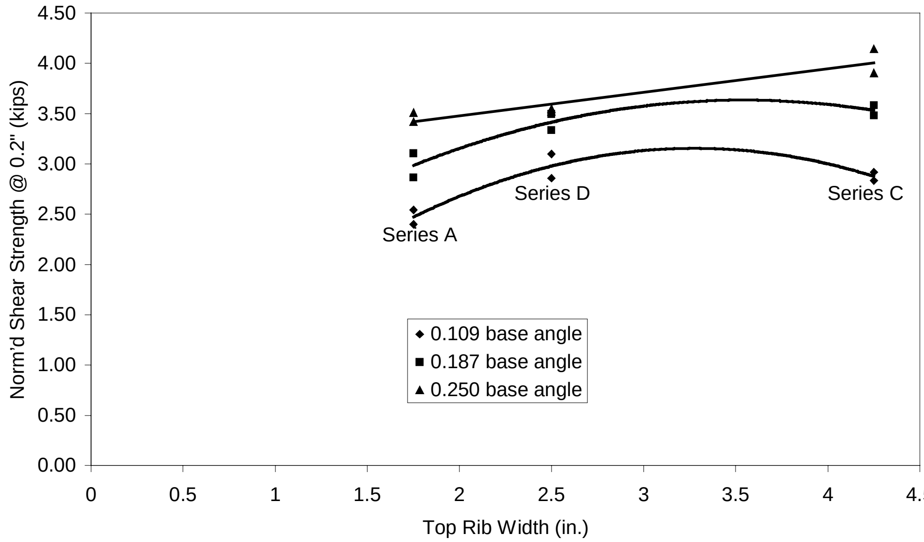

Figure 4.10 Normalized Shear Strength Per Screw at 0.2 in. Slip vs. Top Rib Width

The next two plots, Figures 4.11 and 4.12, contain the relationships between normalized shear strength at 0.2 in. of slip and rib geometry variables. In Figure 4.11, the abscissa is rib area, calculated by multiplying the average rib width by the rib height. In Figure 4.12, the abscissa is the ratio of average rib width to rib height. There is a fairly good linear relationship present in Figure 4.11, suggesting that a greater rib area leads to greater standoff screw shear strength at 0.2 in. of slip. It could be argued, however, that a parabolic curve better fits the data for the case of 0.109 in. thick base angles. A linear trend line for the 0.109 in. base angles was shown because the relationships were linear for the other two sizes of base angles. This relationship is consistent with the conventional belief that a rib with greater area is stiffer than one with less area, so long as the rib width to rib height ratio is within reason. Thus, at low slip values, ribs with greater area yield greater shear strengths for the standoff screws tested in this study.

Few conclusions can be drawn from the plot shown in Figure 4.12. There does not appear to be a consistent relationship between the shear strength of the Elco Grade 8 standoff screw at 0.2 in. of slip and the average rib width to rib height ratio.

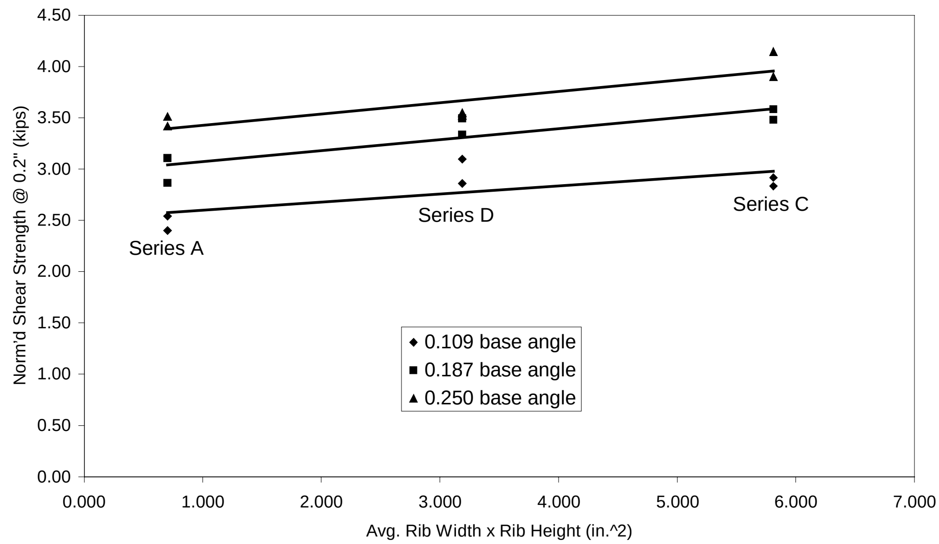

Figure 4.11 Normalized Shear Strength Per Screw at 0.2 in. Slip vs. Rib Area

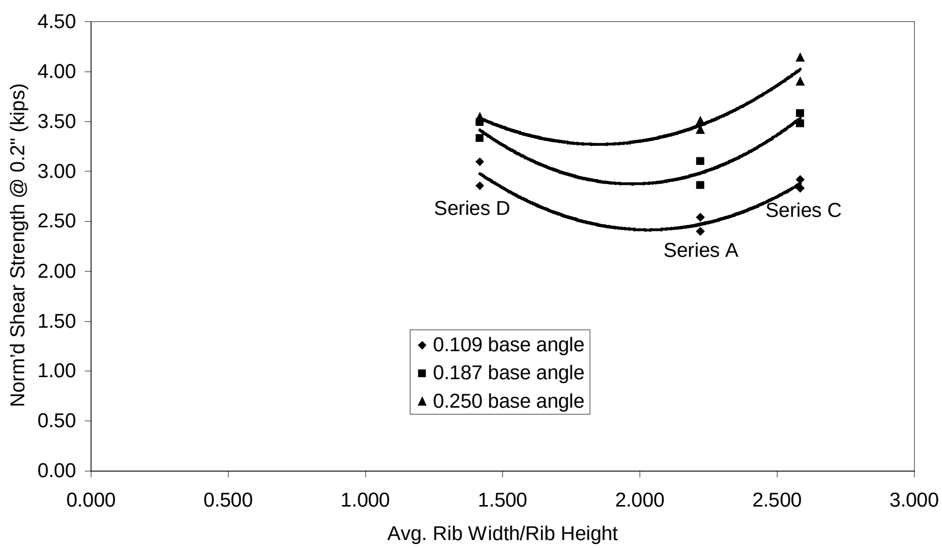

Figure 4.12 Normalized Shear Strength Per Screw at 0.2 in. Slip
vs. Average Rib Width to Rib Height Ratio

It is interesting to note there are some significant differences between the plots of normalized shear strength per screw at 0.2 in. of slip and the plots of normalized ultimate shear strength per screw. These differences are due to the fact that, while flexibility in the base material and in the concrete ribs can increase the ultimate strength of the Elco Grade 8 standoff screw, a stiffer base material and concrete rib leads to greater screw shear strength at low slips. The high slips permitted by the more flexible combinations of deck type and top chord thickness often led to greater ultimate shear strength than did the stiffer combinations. However, this large slip can not be permitted in most full-scale applications. Therefore, the design shear load of the Elco Grade 8 standoff screw should be based on a deflection limit rather than a strength limit.

The most glaring differences between the two groups are in the plots relating shear strength to top chord thickness, average rib width to rib height ratio, and rib area. It is apparent that greater top chord thickness and rib area are beneficial to the shear strength of the standoff screw at low slip values, even though stiffer top chords and concrete ribs can decrease the ultimate shear strength. There also seems to be a direct inverse relation between the ultimate shear strength of standoff screws and the average rib width to rib height ratio. This ratio has no conclusive effect on the shear strength of the standoff screw at low slips.

4.4 Shear Strength of the Elco Grade 8 Standoff Screw

The results and corresponding analysis discussed in Section 4.3 will be used in this section to develop a predictive equation for the shear strength of the Elco Grade 8 standoff screw in profiled steel deck. This equation will be based on the use of the shear strength of the standoff screw that occurs at 0.2 in. of slip.

It can be seen from the charts in Section 4.3 that the two main factors that influence the shear strength of the Elco Grade 8 standoff screw at low slip are top chord thickness and rib area. The relationships shown in Figures 4.8 and 4.11 show that there is a direct linear relationship between each of these two factors and the shear strength of the standoff screw. No definitive conclusions could be drawn regarding the effects of the other parameters discussed in Section 4.3. Therefore, a multiple linear regression was performed on the data represented in Figures 4.8 and 4.11. This data is shown in Table 4.4. Note that the normalized shear strength at 0.2 in. of slip was used to minimize the effects of different concrete compressive strengths. These values were obtained using Eq. 3.1.

Table 4.4 Data Used in First Multiple Linear Regression

Test Number	**Normalized Shear Strength at 0.2" Slip (kips)**	**Rib Area (in.^2)**	**Top Chord Thickness (in.)**
A6-1	2.403	0.704	0.109
A6-2	2.531	0.704	0.109
A7-1	2.916	0.704	0.187
A7-2	3.127	0.704	0.187
A8-1	3.513	0.704	0.250
A8-2	3.413	0.704	0.250
C1-1	2.853	5.813	0.109
C1-2	2.897	5.813	0.109
C2-1	3.455	5.813	0.187
C2-2	3.546	5.813	0.187
C3-1	4.082	5.813	0.250
C3-2	3.720	5.813	0.250
D1-1	3.092	3.188	0.109
D1-2	2.858	3.188	0.109
D2-1	3.438	3.188	0.187
D2-2	3.282	3.188	0.187
D3-1	3.535	3.188	0.250
D3-2	3.487	3.188	0.250

The result of performing a multiple linear regression on the data in Table 4.4 is the following equation.

$$V_s \sqrt{\frac{4000}{f_c'}} = 1.85 + 0.086 A_r + 6.07 t_{TC} \tag{4.1}$$

where:

V_s = shear strength per screw, kips

f_c' = concrete compressive strength, psi

A_r = rib area, in.^{2}

= average rib width $\times$ nominal rib height

t_{TC} = top chord thickness, in.

This equation can be mathematically manipulated so that only the shear strength term is on the left side of the equation.

$$V_s = \sqrt{f_c'}\left(0.0293 + 0.00136 A_r + 0.0960 t_{TC}\right) \qquad (4.2)$$

To evaluate the accuracy of Eq. 4.2, the predicted values obtained from that equation were compared to the experimental values from each test for shear load at 0.2 in. of slip. These predicted values were compared not only with the experimental results from tests with one standoff screw per rib, but with the experimental results from all the tests to make visible any effects that grouping the screws may have at low values of slip. Table 4.5 shows the experimental and predicted shear strength values for each test. Note that Eq. 4.2 is not applicable to the rib failures in test groups D7-D12, as these tests did not reach 0.2 in. of slip. The phenomenon of rib failure is discussed in greater detail in Section 4.5. Note also that Eq. 4.2 was not applied to test groups A3 and A4, in which all four tests failed prematurely by top chord buckling.

It is evident in looking at the ratio of experimental shear strength to predicted shear strength that Eq. 4.2 is a very suitable representation of the shear strength of the Elco Grade 8 standoff screw. As expected, the equation over-estimates the shear strength of the standoff screws in series B. Had these test specimens included adequate reinforcement, a better correlation between experimental and predicted values would have been realized. The equation predicts the shear strength very accurately for series A and C and test groups D1-D6. It can also be deduced from the data in series A and C and groups D1-D6 that the effects of grouping the screws is minimal at low values of slip. The experimental values were plotted versus the predicted values to obtain a visual representation of the accuracy of Eq. 4.1. The result is shown in Figure 4.13, with lines denoting 15% variation between the experimental and predicted. Series B is not included in this figure.

Table 4.5 Predicted Shear Strength at 0.2 in. of Slip (using Eq. 4.2)

Test Number	Deck Type	Screws Per Rib	Rib Area (in.^2)	Top Chord Thickness (in.)	Concrete f'c (psi)	Exper. Shear Strength Per Screw at 0.2" Slip (kips)	Predic. Shear Strength Per Screw at 0.2" Slip (kips)	Experimental / Predicted	Failure Mode
A1-1	0.6C	0.5	0.704	0.109	5027	3.119	2.868	1.088	screw pullout
A1-2	0.6C	0.5	0.704	0.109	5027	3.021	2.868	1.053	screw pullout
A1-3	0.6C	0.5	0.704	0.109	5531	3.073	3.008	1.022	screw pullout
A2-1	0.6C	0.5	0.704	0.187	4775	3.623	3.313	1.094	screw shear
A2-2	0.6C	0.5	0.704	0.187	4775	3.513	3.313	1.061	screw shear
A3-1	0.6C	1	0.704	0.109	5491	NA	NA	NA	top chord buckling
A3-2	0.6C	1	0.704	0.109	5491	NA	NA	NA	top chord buckling
A4-1	0.6C	1	0.704	0.187	5491	NA	NA	NA	top chord buckling
A4-2	0.6C	1	0.704	0.187	5491	NA	NA	NA	top chord buckling
A5-1	0.6C	1	0.704	0.250	5491	3.681	4.000	0.920	screw shear
A5-2	0.6C	1	0.704	0.250	5491	3.227	4.000	0.807	screw shear
A6-1	0.6C	1	0.704	0.109	5080	2.708	2.883	0.939	screw pullout
A6-2	0.6C	1	0.704	0.109	5080	2.852	2.883	0.989	screw pullout
A7-1	0.6C	1	0.704	0.187	5080	3.286	3.417	0.962	screw shear
A7-2	0.6C	1	0.704	0.187	5080	3.524	3.417	1.031	screw shear
A8-1	0.6C	1	0.704	0.250	5080	3.959	3.848	1.029	screw shear
A8-2	0.6C	1	0.704	0.250	5080	3.846	3.848	1.000	screw shear
B1-1	1.0C	1	1.875	0.109	4324	2.350	2.768	0.849	screw pullout
B1-2	1.0C	1	1.875	0.109	4324	2.363	2.768	0.854	screw pullout
B2-1	1.0C	1	1.875	0.187	4324	2.730	3.260	0.837	screw shear
B2-2	1.0C	1	1.875	0.187	4324	2.967	3.260	0.910	screw shear
B3-1	1.0C	1	1.875	0.250	4324	2.794	3.658	0.764	screw shear
B3-2	1.0C	1	1.875	0.250	4324	3.029	3.658	0.828	screw shear
B4-1	1.0C	1	1.875	0.109	3780	2.469	2.588	0.954	screw pullout
B4-2	1.0C	1	1.875	0.109	3780	2.373	2.588	0.917	screw pullout
B5-1	1.0C	1	1.875	0.187	3780	2.620	3.048	0.860	screw shear
B5-2	1.0C	1	1.875	0.187	3780	2.967	3.048	0.973	screw shear
B6-1	1.0C	1	1.875	0.250	3780	3.225	3.420	0.943	screw shear
B6-2	1.0C	1	1.875	0.250	3780	3.126	3.420	0.914	screw shear
B7-1	1.0C	1	1.875	0.109	3780	2.215	2.588	0.856	screw pullout
B7-2	1.0C	1	1.875	0.109	3780	2.399	2.588	0.927	screw pullout
B8-1	1.0C	1	1.875	0.187	3780	2.729	3.048	0.895	screw shear
B8-2	1.0C	1	1.875	0.187	3780	2.796	3.048	0.917	screw shear
B9-1	1.0C	1	1.875	0.250	4748	3.088	3.833	0.806	screw shear
B9-2	1.0C	1	1.875	0.250	4748	3.060	3.833	0.798	screw shear
B10-1	1.0C	2	1.875	0.163	4748	2.243	3.257	0.689	screw shear
B10-2	1.0C	2	1.875	0.163	4748	2.218	3.257	0.681	top chord buckling
B11-1	1.0C	2	1.875	0.313	4775	2.706	4.262	0.635	screw shear
B11-2	1.0C	2	1.875	0.313	4775	3.053	4.262	0.716	screw shear
C1-1	1.5C	1	5.813	0.109	5756	3.423	3.611	0.948	screw shear
C1-2	1.5C	1	5.813	0.109	5756	3.475	3.611	0.962	screw shear
C2-1	1.5C	1	5.813	0.187	5756	4.144	4.180	0.991	screw shear
C2-2	1.5C	1	5.813	0.187	5756	4.254	4.180	1.018	screw shear
C3-1	1.5C	1	5.813	0.250	4310	4.237	4.014	1.056	screw shear
C3-2	1.5C	1	5.813	0.250	4310	3.861	4.014	0.962	screw shear
C4-1	1.5C	2	5.813	0.109	4310	3.260	3.125	1.043	screw shear/pullout
C4-2	1.5C	2	5.813	0.109	4310	3.341	3.125	1.069	screw pullout
C5-1	1.5C	2	5.813	0.187	4310	3.600	3.617	0.995	screw shr./rib failure
C5-2	1.5C	2	5.813	0.187	4310	3.550	3.617	0.981	screw shr./rib failure
C6-1	1.5C	2	5.813	0.250	4310	3.844	4.014	0.958	screw shr./rib failure
C6-2	1.5C	2	5.813	0.250	4310	3.572	4.014	0.890	screw shear
C7-1	1.5C	4	5.813	0.163	4284	3.133	3.455	0.907	screw shr./rib failure
C7-2	1.5C	4	5.813	0.163	4284	3.217	3.455	0.931	screw shear
C8-1	1.5C	4	5.813	0.250	3926	3.670	3.831	0.958	screw shear
C8-2	1.5C	4	5.813	0.250	3926	3.401	3.831	0.888	screw shear
D1-1	1.5VL	1	3.188	0.109	3568	2.920	2.624	1.113	screw pullout
D1-2	1.5VL	1	3.188	0.109	3568	2.699	2.624	1.029	screw pullout
D2-1	1.5VL	1	3.188	0.187	3568	3.247	3.071	1.057	screw shear
D2-2	1.5VL	1	3.188	0.187	3568	3.100	3.071	1.009	screw shear
D3-1	1.5VL	1	3.188	0.250	3568	3.339	3.432	0.973	screw shear
D3-2	1.5VL	1	3.188	0.250	3568	3.293	3.432	0.959	screw shear
D4-1	1.5VL	2	3.188	0.109	3568	2.947	2.624	1.123	screw pullout
D4-2	1.5VL	2	3.188	0.109	3568	2.811	2.624	1.071	screw pullout
D5-1	1.5VL	2	3.188	0.187	5372	3.456	3.768	0.917	rib failure
D5-2	1.5VL	2	3.188	0.187	5372	3.236	3.768	0.859	rib failure
D6-1	1.5VL	2	3.188	0.250	5372	3.713	4.212	0.882	rib failure
D6-2	1.5VL	2	3.188	0.250	5372	3.819	4.212	0.907	rib failure
D7-1	1.5VL	4	3.188	0.163	5372	NA	NA	NA	rib failure
D7-2	1.5VL	4	3.188	0.163	5372	NA	NA	NA	rib failure
D8-1	1.5VL	4	3.188	0.250	5372	NA	NA	NA	rib failure
D8-2	1.5VL	4	3.188	0.250	5372	NA	NA	NA	rib failure
D9-1	1.5VL	4	3.188	0.163	5093	NA	NA	NA	rib failure
D9-2	1.5VL	4	3.188	0.163	5093	NA	NA	NA	rib failure
D10-1	1.5VL	4	3.188	0.250	5093	NA	NA	NA	rib failure
D10-2	1.5VL	4	3.188	0.250	5093	NA	NA	NA	rib failure
D11-1	1.5VL	6	3.188	0.163	5093	NA	NA	NA	rib failure
D11-2	1.5VL	6	3.188	0.163	5093	NA	NA	NA	rib failure
D12-1	1.5VL	6	3.188	0.250	5093	NA	NA	NA	rib failure
D12-2	1.5VL	6	3.188	0.250	5093	NA	NA	NA	rib failure

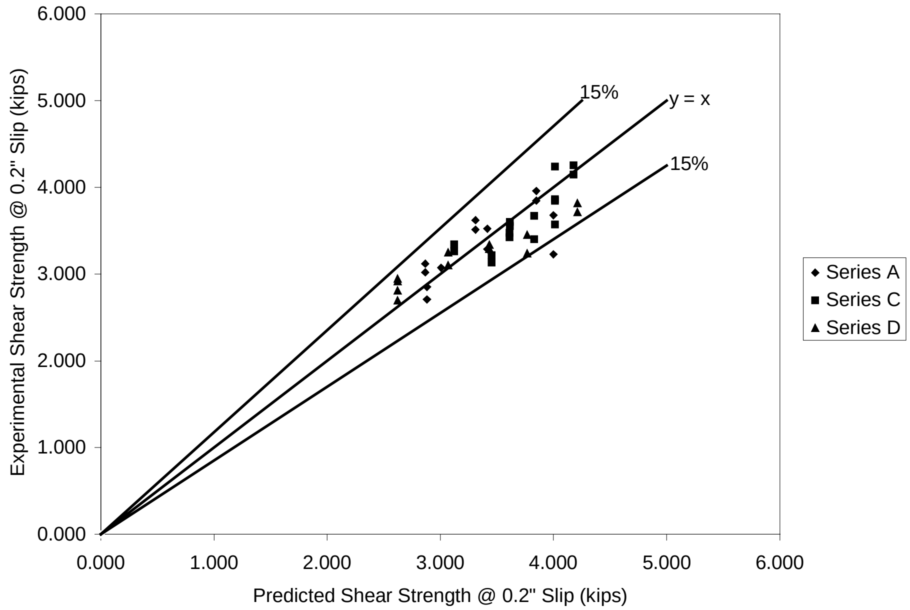

Figure 4.13 Experimental vs. Predicted Shear Strength (using Eq. 4.2)

The accuracy of Eq. 4.2 is supported by Figure 4.13, with only one data point falling outside the 15 percent boundary. In addition, the data points are fairly evenly distributed above and below the line *y=x*.

Because the effects of grouping the standoff screws are minimal at low slips, a second multiple linear regression was performed to improve the accuracy of the predictive equation. This regression included the data from each test that failed by a screw-related behavior, i.e. screw shear or screw pullout, not just those tests with only one screw per rib. This data is shown in Table 4.6.

Table 4.6 Data Used in Second Multiple Linear Regression

Test Number	Normalized Shear Strength at 0.2" Slip (kips)	Rib Area (in.^2)	Top Chord Thickness (in.)
A1-1	2.782	0.704	0.109
A1-2	2.695	0.704	0.109
A1-3	2.614	0.704	0.109
A2-1	3.316	0.704	0.187
A2-2	3.216	0.704	0.187
A5-1	3.142	0.704	0.250
A5-2	2.754	0.704	0.250
A6-1	2.403	0.704	0.109
A6-2	2.531	0.704	0.109
A7-1	2.916	0.704	0.187
A7-2	3.127	0.704	0.187
A8-1	3.513	0.704	0.250
A8-2	3.413	0.704	0.250
C1-1	2.853	5.813	0.109
C1-2	2.897	5.813	0.109
C2-1	3.455	5.813	0.187
C2-2	3.546	5.813	0.187
C3-1	4.082	5.813	0.250
C3-2	3.720	5.813	0.250
C4-1	3.141	5.813	0.109
C4-2	3.219	5.813	0.109
C5-1	3.468	5.813	0.187
C5-2	3.419	5.813	0.187
C6-1	3.703	5.813	0.250
C6-2	3.441	5.813	0.250
C7-1	3.027	5.813	0.163
C7-2	3.108	5.813	0.163
C8-1	3.704	5.813	0.250
C8-2	3.433	5.813	0.250
D1-1	3.092	3.188	0.109
D1-2	2.858	3.188	0.109
D2-1	3.438	3.188	0.187
D2-2	3.282	3.188	0.187
D3-1	3.535	3.188	0.250
D3-2	3.487	3.188	0.250
D4-1	3.120	3.188	0.109
D4-2	2.976	3.188	0.109

Equation 4.3, shown here, was developed from the multiple linear regression performed on the data contained in Table 4.6.

$$V_s = \sqrt{f_c'}\left(0.034 + 0.0012A_r + 0.068t_{TC}\right) \tag{4.3}$$

The accuracy of Eq. 4.3 was checked in the same manner as was Eq. 4.2, by comparing the experimental values to the predicted values. Table 4.7 shows the new predicted shear strength values at 0.2 in. of slip calculated by Eq. 4.3 along side the experimental values. Similar to Eq. 4.2, Eq. 4.3 overestimates the shear strengths for series B. However, Eq. 4.3 is slightly more accurate than Eq. 4.2 for series A and C and test groups D1-D6. This, of course, is to be expected since Eq. 4.3 is derived from the same set of data it is being evaluated against.

The plot of the experimental shear strength values versus the new predicted values is shown in Figure 4.14. As before, series B is not included in this plot. There appears to be a slightly more even distribution above and below the line *y=x* in Figure 4.14 than in Figure 4.13, which is again to be expected. As in Figure 4.13, there is only one data point that lies outside the 15 percent boundary in Figure 4.14. In conclusion, Eq. 4.3 predicts the shear strength of the Elco Grade 8 standoff screw with notable accuracy for the test configurations in series A, C, and D in which screw-related failures governed. However, there are limitations on the use of Eq. 4.3. 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

Table 4.7 Predicted Shear Strength at 0.2 in. of Slip (using Eq. 4.3)

Test Number	Deck Type	Screws Per Rib	Rib Area (in.^2)	Top Chord Thickness (in.)	Concrete f'c (psi)	Exper. Shear Strength Per Screw at 0.2" Slip (kips)	Predic. Shear Strength Per Screw at 0.2" Slip (kips)	Experimental / Predicted	Failure Mode
A1-1	0.6C	0.5	0.704	0.109	5027	3.119	2.996	1.041	screw pullout
A1-2	0.6C	0.5	0.704	0.109	5027	3.021	2.996	1.008	screw pullout
A1-3	0.6C	0.5	0.704	0.109	5531	3.073	3.143	0.978	screw pullout
A2-1	0.6C	0.5	0.704	0.187	4775	3.623	3.286	1.102	screw shear
A2-2	0.6C	0.5	0.704	0.187	4775	3.513	3.286	1.069	screw shear
A3-1	0.6C	1	0.704	0.109	5491	NA	NA	NA	top chord buckling
A3-2	0.6C	1	0.704	0.109	5491	NA	NA	NA	top chord buckling
A4-1	0.6C	1	0.704	0.187	5491	NA	NA	NA	top chord buckling
A4-2	0.6C	1	0.704	0.187	5491	NA	NA	NA	top chord buckling
A5-1	0.6C	1	0.704	0.250	5491	3.681	3.842	0.958	screw shear
A5-2	0.6C	1	0.704	0.250	5491	3.227	3.842	0.840	screw shear
A6-1	0.6C	1	0.704	0.109	5080	2.708	3.012	0.899	screw pullout
A6-2	0.6C	1	0.704	0.109	5080	2.852	3.012	0.947	screw pullout
A7-1	0.6C	1	0.704	0.187	5080	3.286	3.390	0.969	screw shear
A7-2	0.6C	1	0.704	0.187	5080	3.524	3.390	1.040	screw shear
A8-1	0.6C	1	0.704	0.250	5080	3.959	3.695	1.071	screw shear
A8-2	0.6C	1	0.704	0.250	5080	3.846	3.695	1.041	screw shear
B1-1	1.0C	1	1.875	0.109	4324	2.350	2.871	0.819	screw pullout
B1-2	1.0C	1	1.875	0.109	4324	2.363	2.871	0.823	screw pullout
B2-1	1.0C	1	1.875	0.187	4324	2.730	3.220	0.848	screw shear
B2-2	1.0C	1	1.875	0.187	4324	2.967	3.220	0.921	screw shear
B3-1	1.0C	1	1.875	0.250	4324	2.794	3.502	0.798	screw shear
B3-2	1.0C	1	1.875	0.250	4324	3.029	3.502	0.865	screw shear
B4-1	1.0C	1	1.875	0.109	3780	2.469	2.684	0.920	screw pullout
B4-2	1.0C	1	1.875	0.109	3780	2.373	2.684	0.884	screw pullout
B5-1	1.0C	1	1.875	0.187	3780	2.620	3.011	0.870	screw shear
B5-2	1.0C	1	1.875	0.187	3780	2.967	3.011	0.986	screw shear
B6-1	1.0C	1	1.875	0.250	3780	3.225	3.274	0.985	screw shear
B6-2	1.0C	1	1.875	0.250	3780	3.126	3.274	0.955	screw shear
B7-1	1.0C	1	1.875	0.109	3780	2.215	2.684	0.825	screw pullout
B7-2	1.0C	1	1.875	0.109	3780	2.399	2.684	0.894	screw pullout
B8-1	1.0C	1	1.875	0.187	3780	2.729	3.011	0.906	screw shear
B8-2	1.0C	1	1.875	0.187	3780	2.796	3.011	0.929	screw shear
B9-1	1.0C	1	1.875	0.250	4748	3.088	3.669	0.841	screw shear
B9-2	1.0C	1	1.875	0.250	4748	3.060	3.669	0.834	screw shear
B10-1	1.0C	2	1.875	0.163	4748	2.243	3.262	0.688	screw shear
B10-2	1.0C	2	1.875	0.163	4748	2.218	3.262	0.680	top chord buckling
B11-1	1.0C	2	1.875	0.313	4775	2.706	3.976	0.681	screw shear
B11-2	1.0C	2	1.875	0.313	4775	3.053	3.976	0.768	screw shear
C1-1	1.5C	1	5.813	0.109	5756	3.423	3.671	0.932	screw shear
C1-2	1.5C	1	5.813	0.109	5756	3.475	3.671	0.947	screw shear
C2-1	1.5C	1	5.813	0.187	5756	4.144	4.073	1.017	screw shear
C2-2	1.5C	1	5.813	0.187	5756	4.254	4.073	1.044	screw shear
C3-1	1.5C	1	5.813	0.250	4310	4.237	3.806	1.113	screw shear
C3-2	1.5C	1	5.813	0.250	4310	3.861	3.806	1.014	screw shear
C4-1	1.5C	2	5.813	0.109	4310	3.260	3.177	1.026	screw shear/pullout
C4-2	1.5C	2	5.813	0.109	4310	3.341	3.177	1.052	screw pullout
C5-1	1.5C	2	5.813	0.187	4310	3.600	3.525	1.021	screw shr./rib failure
C5-2	1.5C	2	5.813	0.187	4310	3.550	3.525	1.007	screw shr./rib failure
C6-1	1.5C	2	5.813	0.250	4310	3.844	3.806	1.010	screw shr./rib failure
C6-2	1.5C	2	5.813	0.250	4310	3.572	3.806	0.938	screw shear
C7-1	1.5C	4	5.813	0.163	4284	3.133	3.407	0.919	screw shr./rib failure
C7-2	1.5C	4	5.813	0.163	4284	3.217	3.407	0.944	screw shear
C8-1	1.5C	4	5.813	0.250	3926	3.670	3.633	1.010	screw shear
C8-2	1.5C	4	5.813	0.250	3926	3.401	3.633	0.936	screw shear
D1-1	1.5VL	1	3.188	0.109	3568	2.920	2.702	1.081	screw pullout
D1-2	1.5VL	1	3.188	0.109	3568	2.699	2.702	0.999	screw pullout
D2-1	1.5VL	1	3.188	0.187	3568	3.247	3.019	1.076	screw shear
D2-2	1.5VL	1	3.188	0.187	3568	3.100	3.019	1.027	screw shear
D3-1	1.5VL	1	3.188	0.250	3568	3.339	3.275	1.020	screw shear
D3-2	1.5VL	1	3.188	0.250	3568	3.293	3.275	1.006	screw shear
D4-1	1.5VL	2	3.188	0.109	3568	2.947	2.702	1.091	screw pullout
D4-2	1.5VL	2	3.188	0.109	3568	2.811	2.702	1.040	screw pullout
D5-1	1.5VL	2	3.188	0.187	5372	3.456	3.704	0.933	rib failure
D5-2	1.5VL	2	3.188	0.187	5372	3.236	3.704	0.873	rib failure
D6-1	1.5VL	2	3.188	0.250	5372	3.713	4.018	0.924	rib failure
D6-2	1.5VL	2	3.188	0.250	5372	3.819	4.018	0.950	rib failure
D7-1	1.5VL	4	3.188	0.163	5372	NA	NA	NA	rib failure
D7-2	1.5VL	4	3.188	0.163	5372	NA	NA	NA	rib failure
D8-1	1.5VL	4	3.188	0.250	5372	NA	NA	NA	rib failure
D8-2	1.5VL	4	3.188	0.250	5372	NA	NA	NA	rib failure
D9-1	1.5VL	4	3.188	0.163	5093	NA	NA	NA	rib failure
D9-2	1.5VL	4	3.188	0.163	5093	NA	NA	NA	rib failure
D10-1	1.5VL	4	3.188	0.250	5093	NA	NA	NA	rib failure
D10-2	1.5VL	4	3.188	0.250	5093	NA	NA	NA	rib failure
D11-1	1.5VL	6	3.188	0.163	5093	NA	NA	NA	rib failure
D11-2	1.5VL	6	3.188	0.163	5093	NA	NA	NA	rib failure
D12-1	1.5VL	6	3.188	0.250	5093	NA	NA	NA	rib failure
D12-2	1.5VL	6	3.188	0.250	5093	NA	NA	NA	rib failure

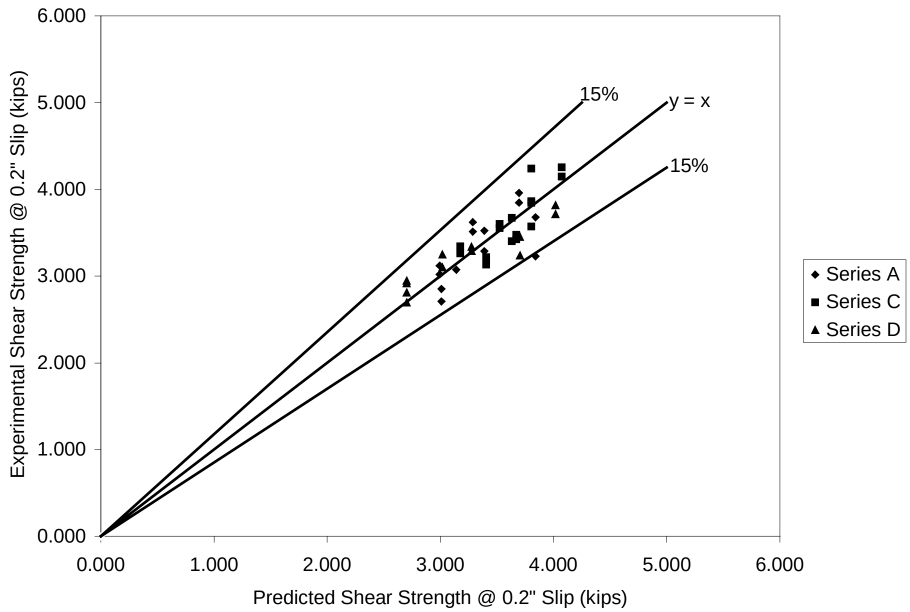

Figure 4.14 Experimental vs. Predicted Shear Strength (using Eq. 4.3)

4.5 Effects of Rib Failure on the Shear Strength of Standoff Screws

Sixteen tests performed in this study were observed to fail by rib failure alone. Rib failure was observed to a lesser extent in four other tests, as well. Equation 4.3, used to predict the shear strength of the Elco Grade 8 standoff screw, can not be used in cases where rib failure is the governing failure mode. This is because rib failure is a concrete-related failure and Eq. 4.3 is based on screw-related failures. Generally, rib failure is a brittle failure compared to the more ductile failure modes of screw shear and screw pullout. For this reason, rib failure is not an acceptable failure mode and a procedure must be developed to determine the shear load at which rib failure occurs. This value can be compared to the theoretical screw shear strength of standoff screws to determine the maximum number of screws that can be placed in a single deck rib for a particular deck type before rib shear will occur.

The most severe cases of rib failure were experienced in each test in groups D7 through D12. These tests contained at least 4 screws per rib and failed at very low values of slip (i.e. less than 0.2 in.). This low slip prevents the applicability of the predictive equation for the shear strength of the Elco Grade 8 standoff screw, Eq. 4.3, which assumes the ultimate shear strength occurs at 0.2 in. of slip.

The tests in groups D5 and D6 also failed by rib failure, but in these tests, the failure was more ductile. Tests in groups D5 and D6 failed at significantly higher average slip and contained only 2 screws per rib (see Table 3.9). Rib failure was observed to a lesser extent in tests C5-1, C5-2, C6-1, and C7-1, with these tests failing at high average slip in a ductile manner (see Table 3.7). In addition, instances of screw shear were evident in nearly all of these tests, indicating that the screw shear strength and concrete rib shear strength were nearly equal. Therefore, despite the existence of some rib failures in these tests, the predictive equation presented earlier is applicable due to the ductile nature of the system.

As mentioned earlier, the rib failures observed in this study did not extend the entire width of the specimen; they could be considered very wide wedge-shaped concrete cone failures. Because Hankins (1994) equation for the shear strength of the Elco Grade 8 standoff screw is based on a wedge-shaped cone failure surface, it could be modified to predict the shear load at which rib failure occurs. The original form of the equation, as discussed in Section 1.2, is given by:

$$V_{wc} = 0.11\sqrt{A_{wc}\sqrt{f'_c}} \tag{1.4}$$

where:

V_{wc} = connector strength, kips

A_{wc} = surface area of wedge shaped tensile concrete pullout cone, in.^{2}

$$= 2w_{r2}\sqrt{\frac{w_{r2}^2}{4} + (H_s - h_r)^2} + w_{r2}\sqrt{w_{r2}^2 + 2(H_s - h_r)^2} + 2w_{r1}\sqrt{3h_r^2}$$

f'_c = concrete compressive strength, psi

h_r = nominal rib height of steel deck, in.

H_s = height of shear connector, in.

w_{r1} = concrete rib width at bottom of flange of steel deck, in.

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

The term A_{wc} represents the wedge-shaped concrete cone failure surface and was developed by Lloyd and Wright (1990). This term must be altered to represent the much wider concrete failure surface observed in the tests experiencing rib failure. Lloyd and Wright (1990) developed an equation to represent the rib shear failure surface that is a modification of the wedge-shaped concrete cone model. This model is discussed in Section 1.2 and is defined as:

$$A_{rs} = w_{r2}\sqrt{\frac{b^2}{4} + \left(H_s - h_r\right)^2} + b\sqrt{\frac{w_{r2}^2}{4} + \left(H_s - h_r\right)^2} \qquad (1.10)$$

where:

A_{rs} = rib shear failure surface area, in.^{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.

This term for the rib shear failure surface area can be used in place of the wedge-shaped cone failure surface in Hankins' equation to estimate the rib shear failure load. Equation 4.4 is Hankins' original equation with the term A_{rs} substituted for A_{wc}.

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

where:

V_{rs} = rib shear strength, kips

A_{rs} = rib shear failure surface area, in.^{2}

f'_c = concrete compressive strength, psi

The term, b, which represents the width of the concrete rib, must be assumed since the failures observed in this study did not extend the full width of the rib. For series D, the failure width was approximately 24 in. and b was assumed accordingly; for series C, it was 18 in. The rib failure surface area term also included the area of concrete that sheared off between the ribs in series D. This area was generally about 6 in. wide and the distance between ribs for 1.5VL deck is 3.5 in. Therefore, 21 in.^{2} were added to the surface area value for the series D predicted rib shear strength values. The rib shear areas can be seen in the summary sheets in the data report (Alander, et al 1998b).

The value obtained from the modified Hankins equation (Eq. 4.4) yields a failure load for one rib and therefore must be multiplied by ten for the cases of 1.5C and 1.5VL decks (because these specimens contained five ribs in each half) to obtain the rib shear failure load for the entire specimen. The values obtained from Hankins' modified equation are shown in Table 4.8 along with the experimental values obtained from the tests in series C and D, the only series in which rib failure was encountered.

Table 4.8 Rib Shear Failure Loads, Series C and D

Test Number	Deck Type	Screws Per Rib	Top Chord Thickness (in.)	Concrete f'c (psi)	Ars (in.^2)	Modified Hankins' Predicted Peak Shear Load (kips)	Peak Shear Load (experimental) (kips)	experimental / predicted	Failure Mode
C1-1	1.5C	1	0.109	5756	85.60	88.64	40.45	0.46	screw shear
C1-2	1.5C	1	0.109	5756	85.60	88.64	40.39	0.46	screw shear
C2-1	1.5C	1	0.187	5756	85.60	88.64	51.63	0.58	screw shear
C2-2	1.5C	1	0.187	5756	85.60	88.64	53.58	0.60	screw shear
C3-1	1.5C	1	0.250	4310	85.60	82.46	46.98	0.57	screw shear
C3-2	1.5C	1	0.250	4310	85.60	82.46	41.08	0.50	screw shear
C4-1	1.5C	2	0.109	4310	85.60	82.46	84.86	1.03	screw shear/pullout
C4-2	1.5C	2	0.109	4310	85.60	82.46	91.33	1.11	screw pullout
C5-1	1.5C	2	0.187	4310	85.60	82.46	109.98	1.33	screw shr./rib failure
C5-2	1.5C	2	0.187	4310	85.60	82.46	113.19	1.37	screw shr./rib failure
C6-1	1.5C	2	0.250	4310	85.60	82.46	91.33	1.11	screw shr./rib failure
C6-2	1.5C	2	0.250	4310	85.60	82.46	82.10	1.00	screw shear
C7-1	1.5C	4	0.163	4284	91.71	85.22	156.15	1.83	screw shr./rib failure
C7-2	1.5C	4	0.163	4284	91.71	85.22	189.94	2.23	screw shear
C8-1	1.5C	4	0.250	3926	91.71	83.39	163.25	1.96	screw shear
C8-2	1.5C	4	0.250	3926	91.71	83.39	145.35	1.74	screw shear
D1-1	1.5VL	1	0.109	3568	98.09	84.20	40.89	0.49	screw pullout
D1-2	1.5VL	1	0.109	3568	98.09	84.20	38.82	0.46	screw pullout
D2-1	1.5VL	1	0.187	3568	98.09	84.20	58.04	0.69	screw shear
D2-2	1.5VL	1	0.187	3568	98.09	84.20	55.10	0.65	screw shear
D3-1	1.5VL	1	0.250	3568	98.09	84.20	47.23	0.56	screw shear
D3-2	1.5VL	1	0.250	3568	98.09	84.20	56.16	0.67	screw shear
D4-1	1.5VL	2	0.109	3568	98.09	84.20	82.35	0.98	screw pullout
D4-2	1.5VL	2	0.109	3568	98.09	84.20	79.65	0.95	screw pullout
D5-1	1.5VL	2	0.187	5372	98.09	93.27	109.48	1.17	rib failure
D5-2	1.5VL	2	0.187	5372	98.09	93.27	86.43	0.93	rib failure
D6-1	1.5VL	2	0.250	5372	98.09	93.27	82.04	0.88	rib failure
D6-2	1.5VL	2	0.250	5372	98.09	93.27	82.04	0.88	rib failure
D7-1	1.5VL	4	0.163	5372	98.09	93.27	94.72	1.02	rib failure
D7-2	1.5VL	4	0.163	5372	98.09	93.27	86.31	0.93	rib failure
D8-1	1.5VL	4	0.250	5372	98.09	93.27	100.37	1.08	rib failure
D8-2	1.5VL	4	0.250	5372	98.09	93.27	106.84	1.15	rib failure
D9-1	1.5VL	4	0.163	5093	98.09	92.04	76.63	0.83	rib failure
D9-2	1.5VL	4	0.163	5093	98.09	92.04	90.70	0.99	rib failure
D10-1	1.5VL	4	0.250	5093	98.09	92.04	91.90	1.00	rib failure
D10-2	1.5VL	4	0.250	5093	98.09	92.04	100.75	1.09	rib failure
D11-1	1.5VL	6	0.163	5093	98.09	92.04	95.16	1.03	rib failure
D11-2	1.5VL	6	0.163	5093	98.09	92.04	98.43	1.07	rib failure
D12-1	1.5VL	6	0.250	5093	98.09	92.04	97.74	1.06	rib failure
D12-2	1.5VL	6	0.250	5093	98.09	92.04	115.95	1.26	rib failure

It is clear from Table 4.8 that the modified Hankins' equation is not applicable to the tests with 1.5C deck (series C). However, there is a fairly good correlation between the predicted and experimental peak shear loads for the rib failure cases in series D (groups D5-D12). This is especially important for test groups D7 through D12, as the screw-related shear strength equation, Eq. 4.3, is not applicable and is very inaccurate for these test groups. It appears that the low average rib width to rib height ratio for the 1.5VL deck makes it especially prone to premature brittle rib failure. In contrast, the rib failures observed in series C (1.5C deck) were not as wide and most likely occurred much later in the testing cycle, as the greater slip readings would seem to indicate.

The predicted rib shear failure strength in series D (1.5VL deck) can be divided by the predicted shear strength per screw as calculated by Eq. 4.3 to estimate the maximum number of standoff screws that can be used before rib shear failure becomes a viable failure mode. In general, the calculated maximum number of screws is close to 20, which supports the test results presented for series D. While rib failure did occur in test specimens with as few as 20 total standoff screws, it was not of the brittle nature of the specimens with more than 20 screws. The rib failures observed in the specimens with 40 or 60 total screws were quite brittle and occurred at slippage of less than 0.2 in. The maximum number of screws that can be placed in each deck rib before brittle rib failure occurs is shown for each test in Table 4.9.

This equation is only valid for specimens containing 1.5VL deck and more than 2 standoff screws per rib. It is important to note that Eq. 4.4 is only an estimate of the rib shear failure strength. The assumed width of the concrete failure surface has a significant effect on the rib failure load. Because no method to predict this width has been established, the modified Hankins equation can not be used in practice to predict the rib shear failure strength. This is another reason to ensure that these types of failures do not occur. Therefore, it is strongly recommended that no more than two screws per rib be used in concrete slabs formed with 1.5VL deck. While the rib failures experienced in 1.5C deck were of a more ductile nature, it is nonetheless recommended that no more than four screws be used per rib in 1.5C deck to avoid the premature brittle rib failures observed in some of the tests consisting of 1.5VL deck.

Table 4.9 Maximum Number of Screws Per Rib

Test Number	Deck Type	Number of Screws Per Rib	Total Number of Screws	Concrete f'c (psi)	Top Chord Thickness (in.)	Failure Mode Observed	Vs Eq. 4.3 (kips)	Vrs Eq. 4.4 (kips)	Max. Number of Screws Per Specimen	Max. Number of Screws Per Rib
D1-1	1.5VL	1	10	3568	0.109	screw pullout	2.70	84.20	31.2	3.1
D1-2	1.5VL	1	10	3568	0.109	screw pullout	2.70	84.20	31.2	3.1
D2-1	1.5VL	1	10	3568	0.187	screw shear	3.02	84.20	27.9	2.8
D2-2	1.5VL	1	10	3568	0.187	screw shear	3.02	84.20	27.9	2.8
D3-1	1.5VL	1	10	3568	0.250	screw shear	3.27	84.20	25.7	2.6
D3-2	1.5VL	1	10	3568	0.250	screw shear	3.27	84.20	25.7	2.6
D4-1	1.5VL	2	20	3568	0.109	screw pullout	2.70	84.20	31.2	3.1
D4-2	1.5VL	2	20	3568	0.109	screw pullout	2.70	84.20	31.2	3.1
D5-1	1.5VL	2	20	5372	0.187	rib failure	3.70	93.27	25.2	2.5
D5-2	1.5VL	2	20	5372	0.187	rib failure	3.70	93.27	25.2	2.5
D6-1	1.5VL	2	20	5372	0.250	rib failure	4.02	93.27	23.2	2.3
D6-2	1.5VL	2	20	5372	0.250	rib failure	4.02	93.27	23.2	2.3
D7-1	1.5VL	4	40	5372	0.163	rib failure	3.58	93.27	26.0	2.6
D7-2	1.5VL	4	40	5372	0.163	rib failure	3.58	93.27	26.0	2.6
D8-1	1.5VL	4	40	5372	0.250	rib failure	4.02	93.27	23.2	2.3
D8-2	1.5VL	4	40	5372	0.250	rib failure	4.02	93.27	23.2	2.3
D9-1	1.5VL	4	40	5093	0.163	rib failure	3.49	92.04	26.4	2.6
D9-2	1.5VL	4	40	5093	0.163	rib failure	3.49	92.04	26.4	2.6
D10-1	1.5VL	4	40	5093	0.250	rib failure	3.91	92.04	23.5	2.4
D10-2	1.5VL	4	40	5093	0.250	rib failure	3.91	92.04	23.5	2.4
D11-1	1.5VL	6	60	5093	0.163	rib failure	3.49	92.04	26.4	2.6
D11-2	1.5VL	6	60	5093	0.163	rib failure	3.49	92.04	26.4	2.6
D12-1	1.5VL	6	60	5093	0.250	rib failure	3.91	92.04	23.5	2.4
D12-2	1.5VL	6	60	5093	0.250	rib failure	3.91	92.04	23.5	2.4

4.6 Ultimate Shear Strength of Standoff Screws in Solid Slabs

Preliminary test groups P7 through P10 contained the only solid slab tests performed in this study (9 tests), so an extensive analysis of this data is not justifiable. In addition, as mentioned in Section 1.2, standoff screws would primarily be used in applications utilizing profiled steel deck. However, a brief discussion of the ultimate strength of the Elco Grade 8 standoff screw in solid slab applications is presented in this section.

Equation 4.3, used to predict the shear strength of the Elco Grade 8 standoff screw in concrete slabs formed with profiled metal deck, is not applicable to solid slab configurations. The basis for predicting the shear strength of standoff screws in solid slabs is the failure mode of longitudinal splitting and the amount of transverse reinforcement used to resist this splitting. Longitudinal splitting of the concrete slab was the governing failure mode in all four tests in groups P7 and P8 and was observed to a lesser extent in test groups P9 and P10. Unlike in slabs formed with profiled steel deck, local crushing of the concrete at the base of the standoff screw can not occur without some extent of longitudinal splitting in solid slabs.

To predict the shear strength of the standoff screws in solid slabs, the resistance of the slab to longitudinal shear must be calculated. The British Steel Construction Institute has adopted the following equation to calculate the shear resistance per unit length of each shear plane along a beam (*Commentary on* 1990):

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

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 each 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)

The shear resistance per unit length, v_r, 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. When this equation is applied to the test parameters of groups P7 through P10 (see Table 2.1), a very close correlation is apparent, as shown in Table 4.10. The peak shear load per standoff screw was determined by dividing the peak shear load by the total number of screws per specimen, in this case 32 screws. The yield strength of the welded wire fabric and the steel reinforcing bars was assumed to be 65 ksi. Test P9-1 is not shown in Table 4.10, as it failed by top chord buckling.

Table 4.10 Predicted Shear Strength in Solid Slab Tests (using Eq. 4.5)

Test Number	Slab Depth (in.)	Slab Length (in.)	A_{cv} (in^2)	A_{sv} (in^2)	Concrete f'c (ksi)	Number of Shear Planes	Total Number Of Screws	Peak Shear Load (experimental) (kips)	Peak Shear Load Per Screw (experimental) (kips)	Peak Shear Load (predicted) (kips)	Peak Shear Load Per Screw (predicted) (kips)	V experimental / V predicted
P7-1	3	36	108	0.000	5.352	4 (2 ea. half)	32	83.92	2.62	86.70	2.71	0.97
P7-2	3	36	108	0.000	5.352	4 (2 ea. half)	32	77.26	2.41	86.70	2.71	0.89
P8-1	3	36	108	0.240	5.352	4 (2 ea. half)	32	131.72	4.12	130.38	4.07	1.01
P8-2	3	36	108	0.240	5.352	4 (2 ea. half)	32	127.07	3.97	130.38	4.07	0.97
P9-2	3	36	108	0.633	5.352	4 (2 ea. half)	32	204.64	6.40	201.85	6.31	1.01
P9-3	3	36	108	0.633	5.352	4 (2 ea. half)	32	204.64	6.40	201.85	6.31	1.01
P10-1	3	36	108	1.025	3.236	4 (2 ea. half)	32	231.59	7.24	239.05	7.47	0.97
P10-2	3	36	108	1.025	3.236	4 (2 ea. half)	32	233.29	7.29	239.05	7.47	0.98

It would appear from Eq. 4.5 that the number of standoff screws per specimen has no influence on the shear resistance of the test specimen. However, there is a limit as to the shear strength of the Elco Grade 8 standoff screw based on the material properties of the screw itself. Therefore, the peak shear load attained per test specimen may be quite different with a significantly lesser number of standoff screws. This model is based on longitudinal splitting of the concrete slab. If too few screws are present to induce longitudinal splitting to some extent, then Eq. 4.5 is not valid.

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 to ensure that longitudinal splitting would be the governing failure mode.