# Chapter 1

# Introduction

## 1.1. General

Over 3500 tests from several countries were considered to develop the current provisions for the shear strength of screw connections in the North American Specification for the Design of Cold-Formed Steel Members (Pekoz 1989). However, none of the tests considered the possibility of insulation being sandwiched between the steel deck profile and the supporting structural member, as is common practice. This study compares 455 elemental tests to Section E4.3 of the North American Specification (2001) and eight confirmatory diaphragm tests to "A Primer on Diaphragm Design" (Luttrell and Mattingly 2004) and proposes the necessary modifications required for the presence of insulation.

## 1.2. Current Specifications

Section E4.3 of the North American Specification for the Design of Cold-Formed Steel Members now states that the shear strength per screw shall be determined as follows:

For $t_2 / t_1 \leq 1.0$, $P_{ns}$ shall be taken as the smallest of

$$P_{ns} = 4.2(t_2^3 d)^{1/2} F_{u2} \tag{1.1}$$

$$P_{ns} = 2.7\ t_1 d\ F_{u1} \tag{1.2}$$

$$P_{ns} = 2.7\ t_2 d\ F_{u2} \tag{1.3}$$

For $t_2 / t_1 \geq 2.5$, $P_{ns}$ shall be taken as the smallest of

$$P_{ns} = 2.7\ t_1 d\ F_{u1} \tag{1.4}$$

$$P_{ns} = 2.7\ t_2 d\ F_{u2} \tag{1.5}$$

For $1.0 < t_2 / t_1 < 2.5$, $P_{ns}$ shall be determined by linear interpolation between the above two cases.

where:

$d$ = nominal screw diameter
$t_1$ = thickness of member in contact with screw head
$t_2$ = thickness of member not in contact with screw head
$F_{u1}$ = tensile strength of member in contact with screw head
$F_{u2}$ = tensile strength of member not in contact with screw head

Because the North American Specification (2001) does not provide a method to determine diaphragm shear strength, the Metal Construction Association method outlined in “A Primer on Diaphragm Design” (Luttrell and Mattingly 2004) was used to predict the shear strength for the confirmatory diaphragm tests. This document was based on the Second Edition of the Steel Deck Institute Diaphragm Design Manual (Luttrell 1987) with certain modifications made for items such as insulation. Each publication uses equations based on the interaction of the systems “supporting frame, the covering panels, and the interconnecting devices or fasteners” to predict the shear strength of the diaphragm at failure (Luttrell 1987).

The method used by the Metal Construction Association (MCA) bases one of the limit states for shear strength of screw connections on Section E4.3 of the North American Specification. The entire procedure for the MCA method is outlined in Section 4.3.1. of this report

## 1.3. Development of Specification

European recommendations were used as a basis to derive provisions for the North American Specification. In a study by Teoman Pekoz (1989), 3500 tests from the United States, Canada, Sweden and the Netherlands were analyzed to determine the necessary modifications to the European Recommendations. The provisions for the European Recommendations (1987) for the shear strength of screw connections at the time were as follows:

a) for $t_2 / t_1 = 1.0$ the smaller of

$$P_{ns} = 3.2(t_1^3 d)^{1/2} F_y \tag{1.6}$$

$$P_{ns} = 2.1\, t_1 d\, F_y \tag{1.7}$$

b) for $t_2 / t_1 \geq 2.5$

$$P_{ns} = 2.1\, t_1 d\, F_y \tag{1.8}$$

c) for $1.0 < t_2 / t_1 < 2.5$

$P_{ns}$ may be taken by linear interpolation between the above two cases.

In the above equations, $t_1$ is the thickness of the material in contact with the screw head, $t_2$ is the thickness of the other member, and d is thread diameter. The equations could be used with any consistent unit system

The above equations account for the possibility of tilting and subsequent pull-out of the screw, and bearing of the metal plates. Screw shear data is available from the manufacturer.

Three major modifications to the European Recommendations were presented by Pekoz (1990). The first was to switch from using the yield strength to using the ultimate strength. A large number of test results were checked and it was found that $F_u$ "gave significantly better correlation." The second was to multiply the coefficients in the equations by a factor of 1.3. It was shown that with this alteration, the values of the ratio of the test results to the predicted results were much closer to 1.0. The last recommendation was to decrease the resistance factor from 0.65 to 0.5. This change was to compensate for the increase in the equation's coefficients.

The recommendations were approved for use in the North American Specification with one noticeable change. In all of the tests studied by Pekoz (1989), the thinner of the different thicknesses of elements was always in contact with the screw head. To provide for a more general application of the standards, the thinner material can or can not be in contact with the screw head. Therefore, bearing failures are checked for both elements while tilting failure is only dependent on the member not in contact with the screw head. Screw shear is dealt with by forcing $P_{ns} = 0.8P_{ss}$, where $P_{ns}$ is the nominal strength of the screw and $P_{ss}$ is the nominal shear strength of the screw according to the manufacturer.

## 1.4. Review of Past Research

Cold-formed steel diaphragms have been in use for many years. Research has focused mainly on the types of sections and the connections used to attach the steel deck to the supporting structural members. These connections have been mainly welds, screws, and power actuated fasteners. Much research has been done to establish the strength of these connections, especially screws, but little to no research has been done on how insulation placed between the steel deck profile and the supporting structural member affects the shear and tensile strength of screw connections

The most useful material was that mentioned previously: the North American Specification for the Design of Cold-Formed Steel Members (*North American* 2001) and the paper presented by Pekoz (1990). Section E4.3 of the North American Specification shows the guidelines now used by industry and are stated previously. All elemental tests conducted for this project were compared to this guideline. The paper by Pekoz was used to derive this specification and was based on the European Recommendations. This material was also very beneficial in giving overall knowledge to the project.

The paper presented by Pekoz (1990) was a revision of an earlier report also written by Pekoz (1989). While Pekoz did not perform any tests for the proposal, he used data from four main sources. The data in these sources were compared to the European Recommendations so that appropriate changes could be proposed to AISI.

The first set of data used by Pekoz was from the Illinois Tool Works (Pekoz 1989). In this study, 940 standard lap-joint 2 screw tests were conducted with material ranging from #6 to #14 self-drilling screws and 0.018 in. to 0.188 in. steel sheet. All screws were hex washer head TEKS. The reference only noted the ultimate strength of the material and did not indicate the mode of failure, only the maximum load. It was noted that screw shear occurred on a few of the tests that involved thicker gages. In all of the tests, the thinner of the two steel sheets was always in contact with the screw head.

The test results were presented in plots for each screw size, a sample of which can be seen in Fig 1.1. With these results, an additional plot of $P_{test}/P_{cal}$ vs $t_{min}$ was made, where $P_{cal}$ was based on the ultimate strength of the material, to see if the test values were above the predicted values. The plot confirmed that the equations were conservative with most of the points being above 1.0.

Another reference used was from the Dofasco Corporation (Eastman 1976). This study included 960 standard lap-joint 2 screw tests of which 162 were under cyclic loads. The material ranged from #8 to #14 self-drilling screws and 0.025 in. to 0.060 in. steel sheet. As in the previous reference, screw shear did occur when thicker gages were used but these were indicated. Both yield and ultimate strengths were reported.

The results were presented in plots similar to Fig 1.1. With these results, additional plots of $P_{test}/P_{cal}$ vs $t_{min}$ were made, where $P_{cal}$ was based on the ultimate strength in one plot and the yield strength of the material in another, to see if the test values were above the predicted values. The plots confirmed that the equations were conservative with most of the points being above 1.0 and that using the ultimate strength produced less scatter.

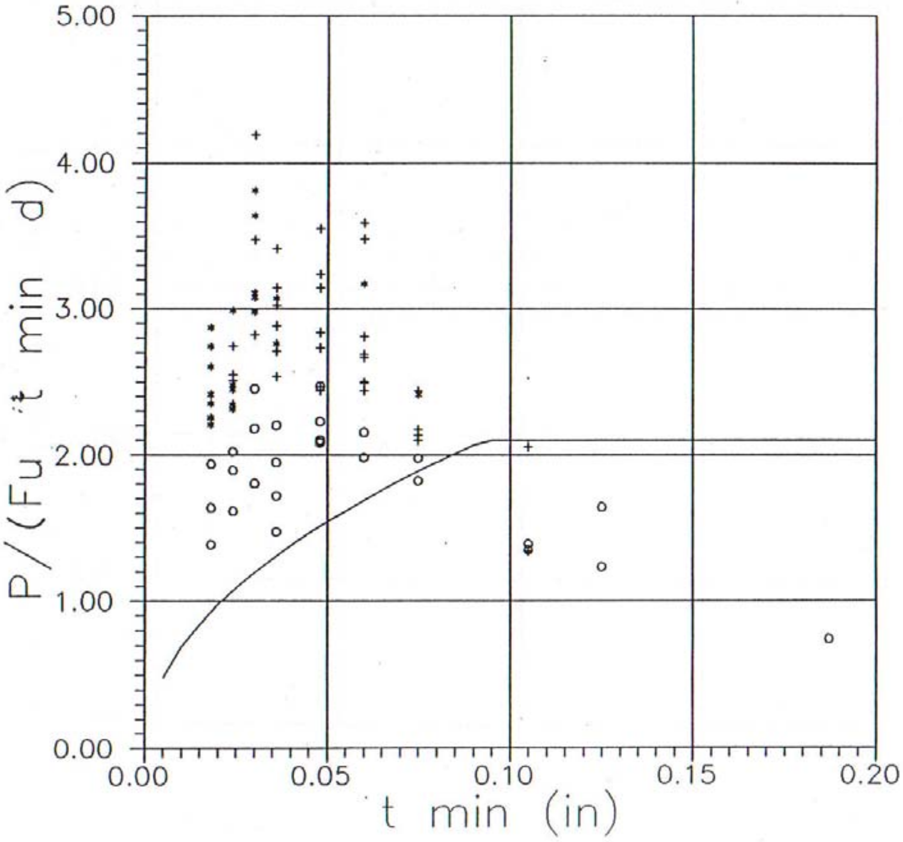

**Figure 1.1 Sample of Test Results (*Pekoz, 1989*)**

The third source of screw shear data was from a report to the Swedish Building Research Institute (Berggren et al. 1971). The study included results from 105 standard lap-joint tests on steel sheet and 54 standard lap-joint tests on aluminum. The tests used specimens held together with one or two screws. The material ranged from #4 to #14 self-drilling screws and 0.028 in. to 0.200 in. steel sheet. Screw shear occurred when thicker gages were used as in the previous references. Also edge failure occurred in a few samples where the edge distance was less than three times the screw diameter but these were indicated and, along with screw shear, not considered in the analysis. Both yield and ultimate strengths were reported.

The results were presented in plots similar to Fig 1.1 and plots of Force vs Sheet

Thickness. With these results, additional plots of $P_{test}/P_{cal}$ vs $t_{min}$ were made, where $P_{cal}$ was based on the ultimate strength in one plot and the yield strength of the material in another, to see if the test values were above the predicted values. The plots confirmed that the equations were conservative with most of the points being above 1.0 and that using the ultimate strength produced less scatter.

The last source of screw shear data used by Pekoz in his recommendations to AISI was from the Instituut TNO in the Netherlands (Toma 1975). The study included results from 178 standard lap-joint single screw tests, 83 standard lap-joint 2 screw tests, 16 standard lap-joint 2 screw tests where the screws were perpendicular to the direction of the applied force, and 4 double shear tests using a single screw. The material ranged from #6 to #14 self-drilling screws and 0.020 in. to 0.100 in. steel sheet. Screw shear occurred when thicker gages were used as in the previous references. Also edge failure occurred in a few samples where the edge distance was less than three times the screw diameter but these were indicated and, along with screw shear, not considered in the analysis. Both yield and ultimate strengths were reported.

The results were presented in plots similar to Fig 1.1. With these results, additional plots of $P_{test}/P_{cal}$ vs $t_{min}$ were made, where $P_{cal}$ was based on the ultimate strength in one plot and the yield strength of the material in another, to see if the test values were above the predicted values. The plots confirmed that the equations were conservative with most of the points being above 1.0 and that using the ultimate strength produced less scatter.

## 1.5. Objective

The objective of this project is four fold. The first objective is to present results from 455 elemental shear tests conducted at Virginia Tech where a layer of insulation is sandwiched between two steel plates. The plates will be of sufficient thickness and strength to simulate a steel deck and supporting structural member. The second objective is to present results from 12 elemental tension tests where insulation is again sandwiched between two steel plates. The third objective is to present results from two series of diaphragm tests conducted with and without insulation between the deck and purlins. The forth objective is to develop modifications for inclusion in Section E4.3 of the North American Specification for the Design of Cold-Formed Steel Members (*North American* 2001) and “A Primer on Diaphragm Design” (Luttrell and Mattingly 2004).

# Chapter 2

# Elemental Tests

## 2.1. Overview

Elemental tests were conducted to determine if the presence of insulation between two thicknesses of steel deck has any effect on the strength of screw connections connecting the two sheets. A total of 435 standard lap-joint 2 screw shear tests using unfaced fiberglass insulation, 20 standard lap-joint 2 screw shear tests using vinyl faced insulation, and 12 standard single screw tension tests using unfaced fiberglass were conducted.

## 2.2. Coupon Tests

Tensile coupon tests were conducted on three specimens from each plate type received in four separate shipments. A sample of one of the tests is shown in Fig. 2.1. The specimens were machined to the following nominal dimensions:

Length: 8 in. Width: ¾ in. Milled Width: ½ in.

Each specimen's dimensions and loads at failure are reported in Table A1. Painted specimens were cleaned of paint before the thickness was measured, while galvanized specimens had 0.0015 in. subtracted from the measured thickness to account for galvanizing. The tension tests were conducted using a 30 kip load cell in an INSTRON Model 4206-006 screw operated testing machine. Tests were preformed at a speed of 0.1 in./min until failure. A summary of the tensile coupon test results are given in Table 2.1.

Figure 2.1. Coupon Test

Table 2.1. Coupon Test Results

| Shipment | Coating | Thickness (in) | Avg Fy (ksi) | Avg Fu (ksi) |
|---|---|---|---|---|
| 1 | Painted | 0.106 | **NA** | **73.0** |
| 1 | Painted | 0.058 | **NA** | **77.7** |
| 1 | Painted | 0.031 | **NA** | **62.8** |
| 1 | Painted | 0.023 | **NA** | **68.7** |
| 2 | Galvanized | 0.117 | **43.9** | **54.7** |
| 2 | Galvanized | 0.045 | **47.0** | **57.7** |
| 3 | None | 0.057 | **28.0** | **43.5** |
| 3 | Galvanized | 0.044 | **31.4** | **49.2** |
| 3 | None | 0.030 | **30.0** | **49.2** |
| 4 | None | 0.075 | **46.4** | **55.1** |
| 4 | Galvanized | 0.019 | **60.2** | **62.5** |

## 2.3. Gap and Screw Measurements

Because the insulation used in all of the tests was compressible, the thickness of the insulation after compression, or the gap between the steel sheets, was measured. This was done to see if the reduction in strength was a function of uncompressed insulation thickness or of the compressed thickness. It was found that the compressed height of the faced and unfaced insulation varied approximately linearly with the uncompressed thickness.

The gaps of 149 specimens were taken. The distance measured was from the bottom of the lower sheet to the top of the upper sheet beside where each screw was drilled through the specimen, thereby getting a total specimen thickness. The thickness of each sheet was then subtracted from the measured distance to get the height of the compressed insulation. Measurements of 129 specimens containing unfaced insulation were taken, along with measurements of 20 specimens containing faced insulation. These measurements are reported in Tables A2 through A6, while a summary of the measured gaps are given in Table 2.2.

**Table 2.2. Insulation Thicknesses**

| Insulation Thickness (in) | Insulation Type | Gap (in) |
|---|---|---|
| 3 1/4 | Unfaced Fiberglass | 0.093 |
| 4 1/4 | Unfaced Fiberglass | 0.117 |
| 6 3/8 | Unfaced Fiberglass | 0.153 |
| 3 | Faced Fiberglass | 0.089 |
| 6 | Faced Fiberglass | 0.141 |

The diameters of the different size screws used during the element tests were measured and are presented is Table 2.3.

**Table 2.3. Screw Dimensions**

| Screw Size | Shank (in) | Head (in) | Washer (in) |
|---|---|---|---|
| # 8 | 0.164 | 0.338 | 0.495 |
| # 10 | 0.190 | 0.400 | 0.463 |
| # 12 | 0.216 | 0.410 | 0.545 |
| # 14 | 0.240 | 0.500 | 0.610 |

## 2.4. Shear Test Details

### 2.4.1. Test Specimen Configuration

The goal of the elemental tests was to simulate connections where rolled fiberglass insulation is sandwiched between steel deck and purlins, then to compare the experimental shear strengths to those calculated using the current North American Specification (*North American* 2001). The tests were conducted in accordance with the AISI "Test Methods for Mechanically Fastened Cold-Formed Steel Connections" (*Cold-Formed* 1996). Figure 2.2 is a photograph of a test specimen.

All tests were conducted in a single lap configuration using two pieces of steel sheet fastened together with two self-drilling screws. The setup is shown in Fig. 2.3. The recommended geometric proportions of each specimen were followed except for width and length (*Cold-Formed* 1996). The width was reduced from the recommended 2 3/8 in. to 2 in. so that the specimen would fit into a 2 in. grip and still maintain a centerline loading. The same width was also used in another research project sponsored by AISI (Koka 1997) and another by the Canadian Steel Industries Construction Council (Eastman 1976). No problems with edge distance type failures were noticed during testing.

Figure 2.2. Elemental Test

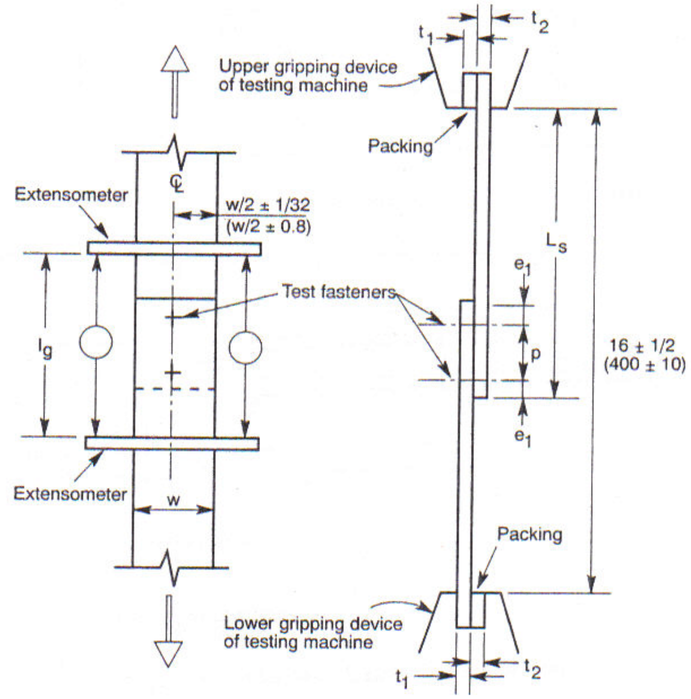

Figure 2.3. Elemental Test Setup (*Cold-Formed*, 2002)

The dimensions used for each specimen were:

$w = 2$ in.
$L_s = 12$ in.
$e_1 = 1\ 3/16$ in.
$p = 2\ 3/8$ in.
$l_g = 10$ in.
$t_1$ and $t_2$ varied

Each test was conducted using an INSTRON Model 4206-006 screw operated testing machine with a speed of 0.18 to 0.3 in. per minute and a MTS Model 632.25F-20 extensometer with extenders. After a maximum load was reached, the load was recorded. No packing shims were required because no tests were preformed where both strips were greater than 0.0625 in. Five repetitions of each configuration were conducted.

### 2.4.2. Test Designation

Seven series of standard lap-joint 2 screw tests were conducted to evaluate the impact of insulation on the shear strength of screw connections in metal decking. Material ranged in thickness from 0.117 in. to 0.019 in. steel sheet, 0 in. to 6 3/8 in. of unfaced fiberglass insulation, and #8 to #14 screws. A detailed test matrix is given in Table A7.

The seven series of test were separated by the use of differing plate thicknesses (nominal 26 ga. to 12 ga.) so that two series were tested where $t_2 = 1.0t_1$ and $1.0t_1 \leq t_2 \leq 2.5t_1$ and three series where $t_2 \geq 2.5t_1$. Each series was then divided further into sets by varying insulation thickness (0, 3 ¼, 4 ¼, 6 $^3/_8$ in.) and screw size (# 8, 10, 12, 14). Five identical tests were then conducted for each configuration. This gave a total of 70 possible tests for each series.

Four sets of standard lap-joint 2 screw tests were conducted to confirm that the presence of vinyl facing does not significantly affect the impact of insulation on the shear strength of screw connections in metal deck. Material ranged in thickness from 0.057 in. (16 ga) to .023 in. (24 ga) steel sheet, 3 in. to 6 in. of faced insulation, and #12 and #14 screws.

Each test was designated by a sequence of numbers, e.g. 2-24x16-4 ¼-12. The first term represented the test number (e.g. 2), the second set was the series number (e.g. 24x16), the third term was the uncompressed insulation thickness in inches (e.g. 4 ¼), and the fourth term was the screw size (e.g. 12). After testing, each sample was marked with the maximum load.

## 2.5. Shear Test Results

The values obtained from the elemental tests using unfaced insulation are presented in Tables A8 through A14, while the results from the element tests using faced insulation are shown in Table 2.4. The five values for each configuration were averaged and divided by two to get the strength per screw so that a direct comparison to the North American Specification (2001) could be made. The blank cells within the tables indicate that the screw sheared before deformation in the steel sheet occurred in that particular configuration. Because the screw's shear strength was not considered in this study, no value was recorded.

**Table 2.4. Shear Test Results with Faced Insulation**

| | | | | | | Test | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $t_1$ | $t_2$ | Screw | Insulation (in) | 1 (kips) | 2 (kips) | 3 (kips) | 4 (kips) | 5 (kips) | Average (kips) | Strength per screw (kips) |
| 0.0295 | 0.0435 | # 12 | 3 | 1.404 | 1.363 | 1.401 | 1.645 | 1.435 | 1.450 | 0.725 |
| 0.0295 | 0.0435 | # 14 | 3 | 1.574 | 1.616 | 1.62 | 1.653 | 1.714 | 1.635 | 0.818 |
| 0.0565 | 0.0565 | # 14 | 6 | 1.988 | 2.184 | 2.211 | 1.965 | 2.108 | 2.091 | 1.046 |
| 0.0230 | 0.0580 | # 14 | 6 | 1.65 | 1.817 | 1.876 | 1.918 | 1.704 | 1.793 | 0.897 |

## 2.6. Tension Test Details

### 2.6.1. Test Specimen Configuration

The goal of the elemental tests was to simulate connections where rolled fiberglass insulation is sandwiched between steel sheet and purlins and to compare the experimental tensile strengths to those predicted using the North American Specification (2001). The tests were conducted to determine if the presence of insulation affects the tensile strength of screw connections.

All tests were standard tension test where two steel sheets were fastened together with one self-drilling screw. The sheets were from the same material used in the shear tests, but were cut to dimensions of 2 in. wide and 6 in. long. These sheets were then bent as shown in Fig. 2.4.

Each test was conducted using an INSTRON Model 4468 screw operated testing machine at a speed of 0.25 in. per minute. After the maximum load was reached, the value was recorded.

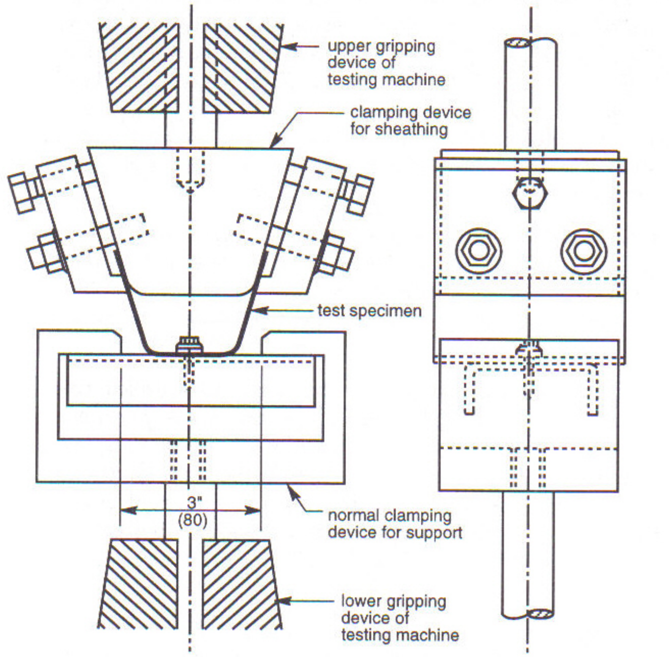

Figure 2.4. Tension Test Setup (*Cold-Formed*, 2002)

### 2.6.2. Test Designation

Two series of standard tension screw tests were conducted to evaluate the impact of insulation on the tensile strength of screw connections in steel sheet. Material ranged in thickness from 0.117 in. (nominal 12 ga) to 0.023 in. (nominal 24 ga) steel sheet, 0 in. to 6 3/8 in. of unfaced fiberglass insulation, and #10 screws. The tests were conducted in accordance with the AISI "Test Methods for Mechanically Fastened Cold-Formed Steel Connections." A photograph of a test specimen is shown in Fig. 2.5.

**Figure 2.5. Tension Test Specimen**

Each test was designated by a sequence of numbers, e.g. 3-24x16-6-10. The first term represents the test number (e.g. 3), the second set was the series number (e.g. 24x16), the third term was the uncompressed insulation thickness in inches (e.g. 6), and the fourth term was the screw size (e.g. 10). After testing, each sample was marked with the maximum load.

## 2.7. Tension Tests Results

The values obtained from the elemental tension tests are presented in Tables 2.5. The three values for each configuration were averaged so that a direct comparison to the North American Specification (2001) could be made.

**Table 2.5. Tension Tests Results**

|  |  |  |  | Test |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| $t_1$ | $t_2$ | Screw | Insulation (in) | 1 (kips) | 2 (kips) | 3 (kips) | Average (kips) | Failure Type |
| 0.023 | 0.0565 | # 10 | 0 | 0.473 | 0.454 | 0.451 | 0.459 | Pull-Out |
| 0.023 | 0.0565 | # 10 | 6 3/8 | 0.431 | 0.446 | 0.414 | 0.430 | Pull-Out |
| 0.0295 | 0.1170 | # 10 | 0 | 1.509 | 1.610 | 1.517 | 1.545 | Pull-Over |
| 0.0295 | 0.1170 | # 10 | 6 3/8 | 1.479 | 1.427 | 1.497 | 1.468 | Pull-Over |

## 2.8. Summary

A total of 435 standard lap-joint 2 screw shear tests using unfaced fiberglass insulation, 20 standard lap-joint 2 screw shear tests using vinyl faced insulation, and 12 standard single screw tension tests using unfaced fiberglass were conducted. These tests were conducted to determine if the presence of insulation between two steel sheets connected by screws reduces the strength of the connection, and to determine if vinyl faced insulation results in a difference in strength from unfaced insulation. The results from these tests are compared to the appropriate section of the North American Specification for the Design of Cold-Formed Steel Members (2001) in Chapter 4 of this report.

## 2.9. Limitations

The results stated in this chapter and the recommendations made later in this report are limited to the material used during testing and the combinations of those materials. The test configurations were derived to cover common metal deck designs and the range of the appropriate equations in the North American Specification (2001). Additional tests may need to be conducted for particular configurations outside of the parameters of this project.

# Chapter 3

# Diaphragm Tests

## 3.1. Overview

Two series of cantilever diaphragm tests were conducted to evaluate the influence of insulation on the strength of the diaphragm. Each series consisted of four tests for a total of eight cantilever diaphragm tests. One series of tests used 0.104 in. thick purlins, 0.018 in. thick steel deck and four different vinyl faced insulation thicknesses (0, 3, 4, 6 in.). The second series of tests used 0.060 in. thick purlins with all other parameters being the same as the first series. The tests were conducted in accordance with the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms" (*Cold-Formed* 1996).

## 3.2. Test Details

### 3.2.1. Test Designation

Each test was designated by a sequence of numbers, e.g. 26x12-4. The first set represents the nominal gauge of the deck and purlins (e.g. 26x12). The second term indicates the uncompressed insulation thickness in inches (e.g. 4).

### 3.2.2. Test Frame Configuration

The cantilever diaphragm test reaction frame, as illustrated in Fig. 3.1, was constructed of four H-shaped sections (W10X30). Nominal plan dimensions were 16 ft by 15 ft center-to-center of parallel web members. The perimeter members were connected with a single-angle at corners B, a double angle at corner C, and a T-section at corner D. A pin was used to connect the frame members at corner A. Member CD was attached to the reaction floor by using pinned base assemblies at locations C and D. In addition, the web was braced at points C and D to minimize rolling of the member, as illustrated in Fig. 3.2. Member AB was supported by rollers at locations A and B. An additional roller assembly was positioned at A on the bottom flange resist uplift of the member, as illustrated in Fig. 3.3. The stiffness of the bare test frame and additional roller assembly was found to contribute less than 1% to the total resistance.

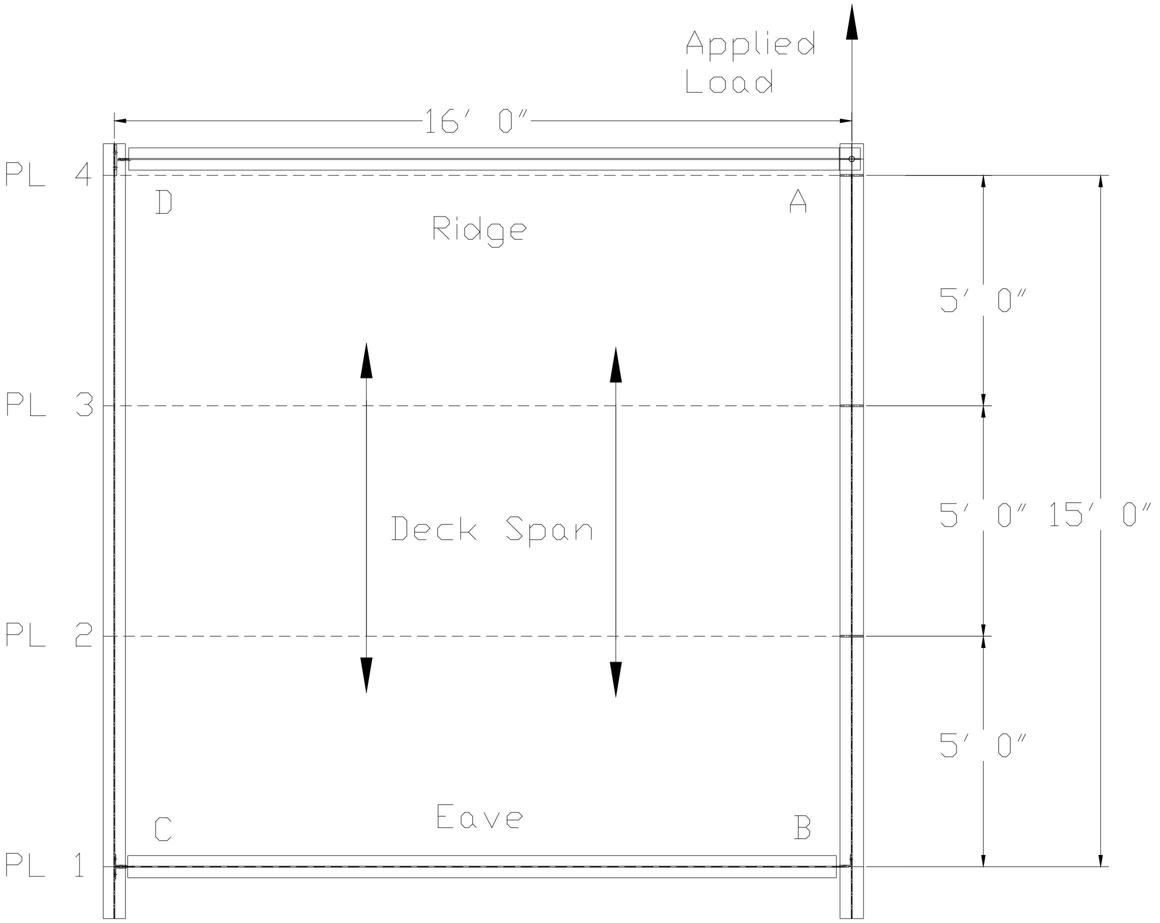

**Figure 3.1. Diaphragm Test Setup (*Piotter and Easterling, 2001*)**

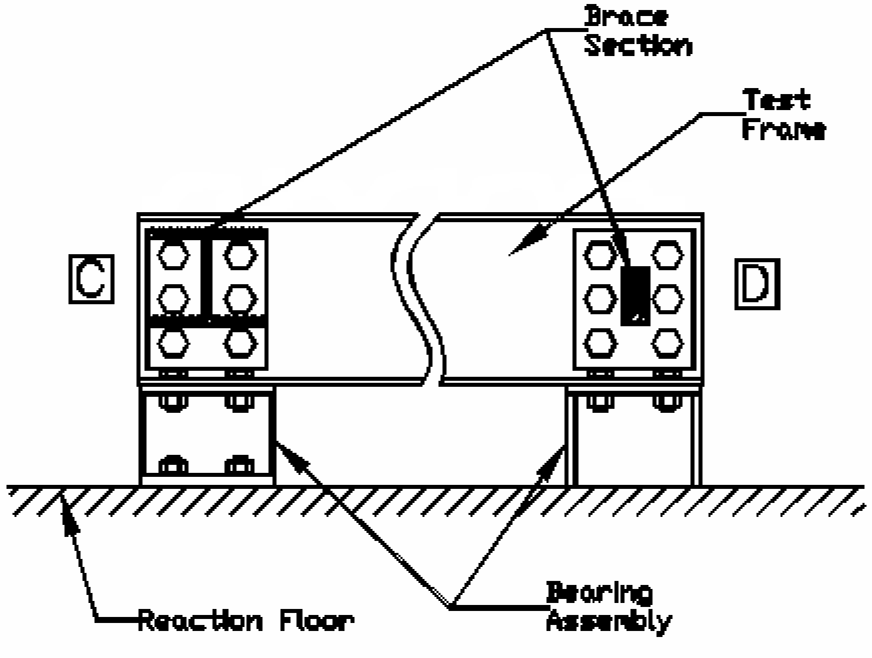

Figure 3.2. Pinned Support Detail (*after Piotter and Esterling, 2001*)

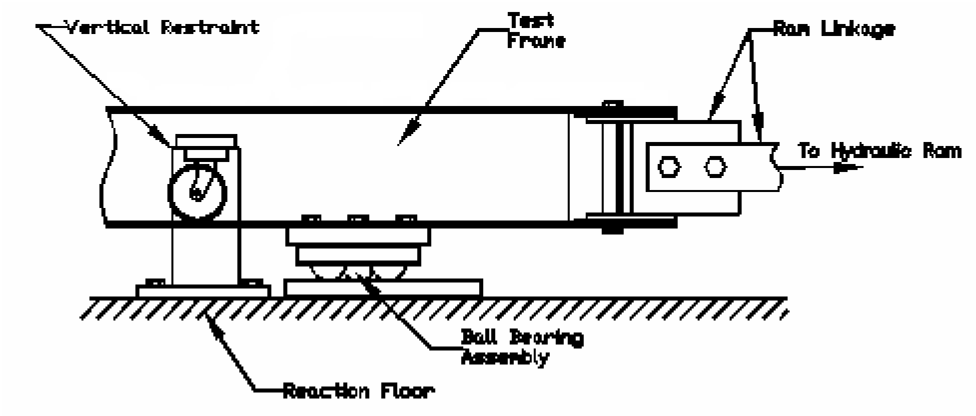

Figure 3.3. Roller support Detail (*after Piotter and Esterling, 2001*)

### 3.2.3. Test Specimen Configuration

The framing configuration for the diaphragm consisted of z-purlins and a channel eave strut. Two purlin thicknesses, 0.104 in. (12 ga) and 0.060 in. (16 ga), were used in combination with two eave strut thicknesses, 0.104 in. (12 ga) and 0.068 in. (14 ga), respectively. All deck used had a thickness of 0.018 in. (26 ga). The diaphragm had three purlins bearing on the reaction frame and bolted to anti-roll clips illustrated in Fig. 3.4. The eave strut was bolted through the bottom flange to member CB.

Two deck lengths were used in each test (10 ft 4 in. and 5 ft 2in.). A 6 in. overlap was provided at pulin line 3 (PL3) with 4 inches upslope and 2 inches downslope as illustrated in Fig. 3.5. The width of the deck panels were either 1.5 or 3 ft for the diaphragm as also illustrated in Fig. 3.5.

The deck fastening pattern was the same in all tests and is shown in Fig. 3.6.

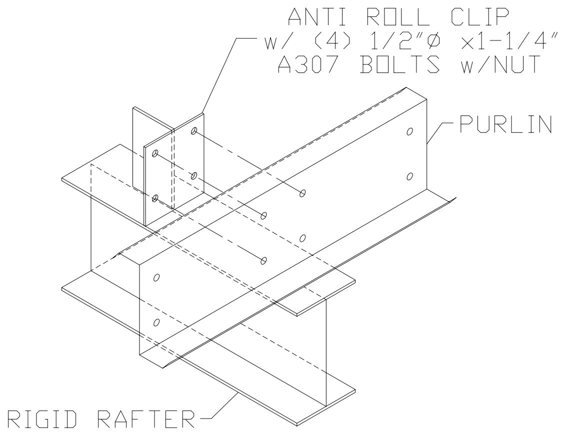

**Figure 3.4. Diaphragm Framing Detail (*Piotter and Easterling, 2001*)**

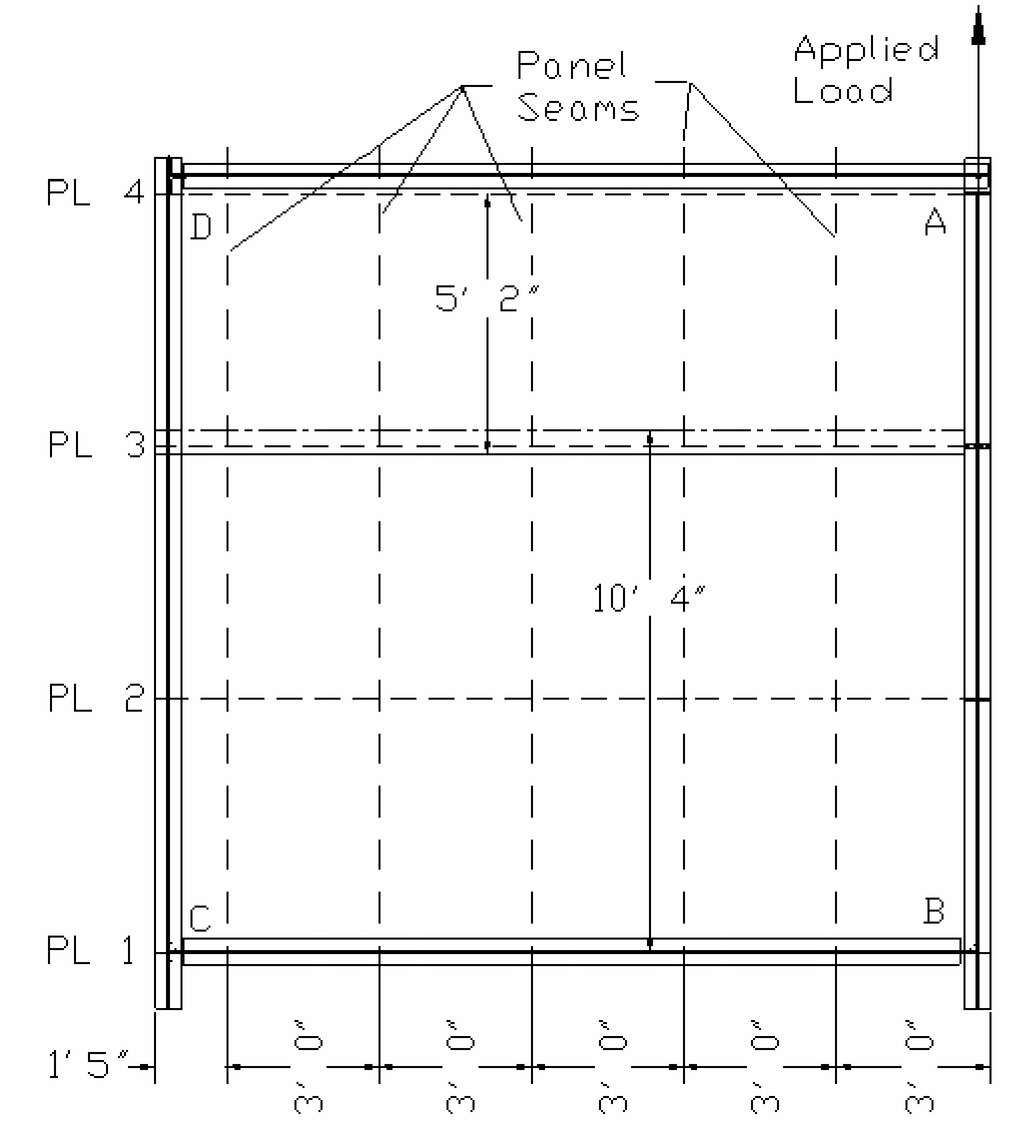

Figure 3.5. Panel Layout (*after Piotter and Esterling, 2001*)

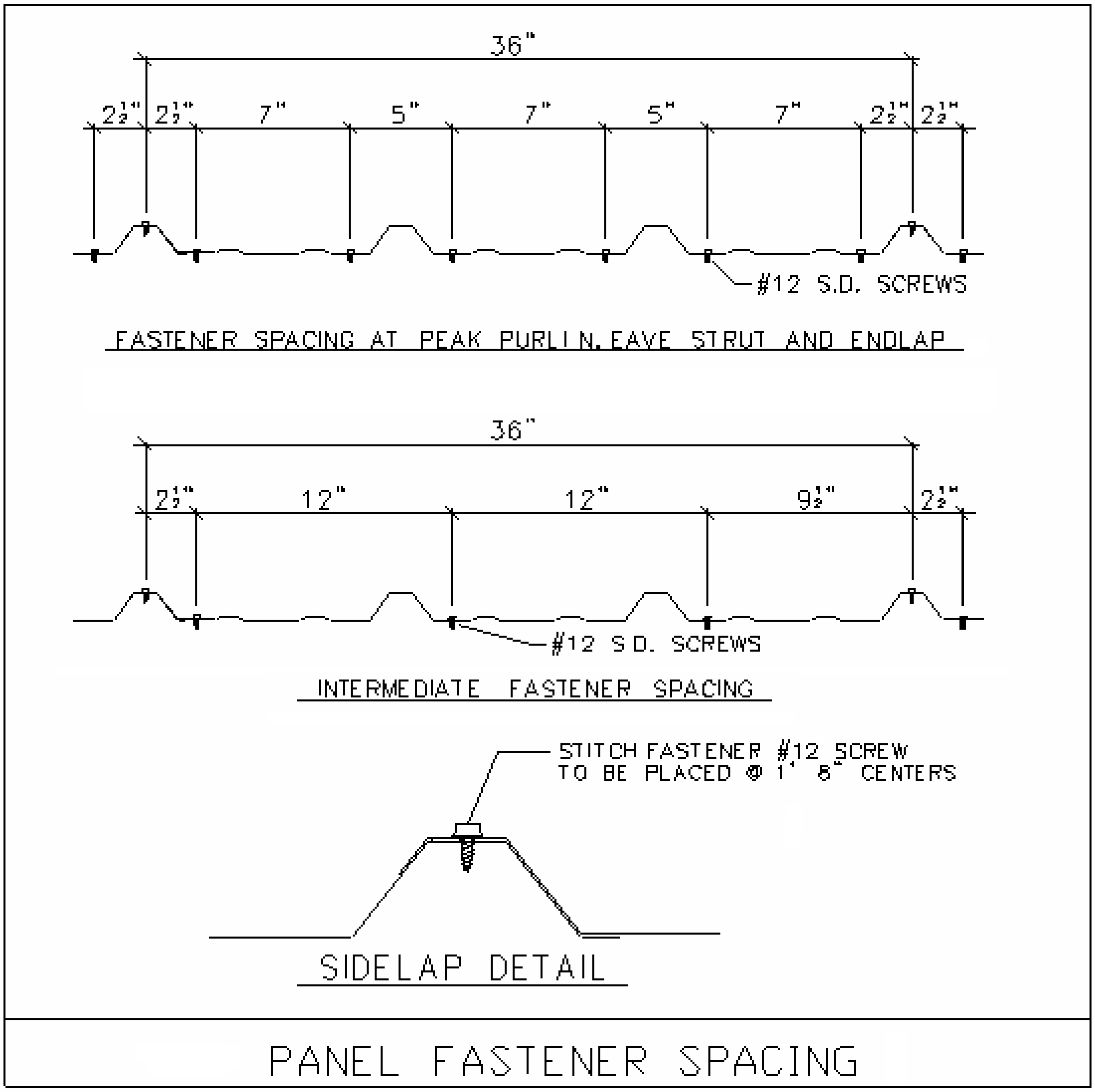

**Figure 3.6. Panel Fastener Spacing (*after Piotter and Esterling, 2001*)**

### 3.2.4. Loading and Measurements

As illustrated in Fig. 3.1, load was applied to the test setup at corner A. Load was applied by a 30 kip hydraulic ram attached to the reaction floor. Load was measured with a 20 kip load cell, which connected the frame to the hydraulic ram.

Frame displacements were measured during each test by four displacement transducers. Transducer locations are shown in Fig. 3.7 and are identical in designation to the AISI canilever diaphragm method. The load and all displacements were recorded for each test at various points using a Measurements Group System 6000 Data Acquisition System.

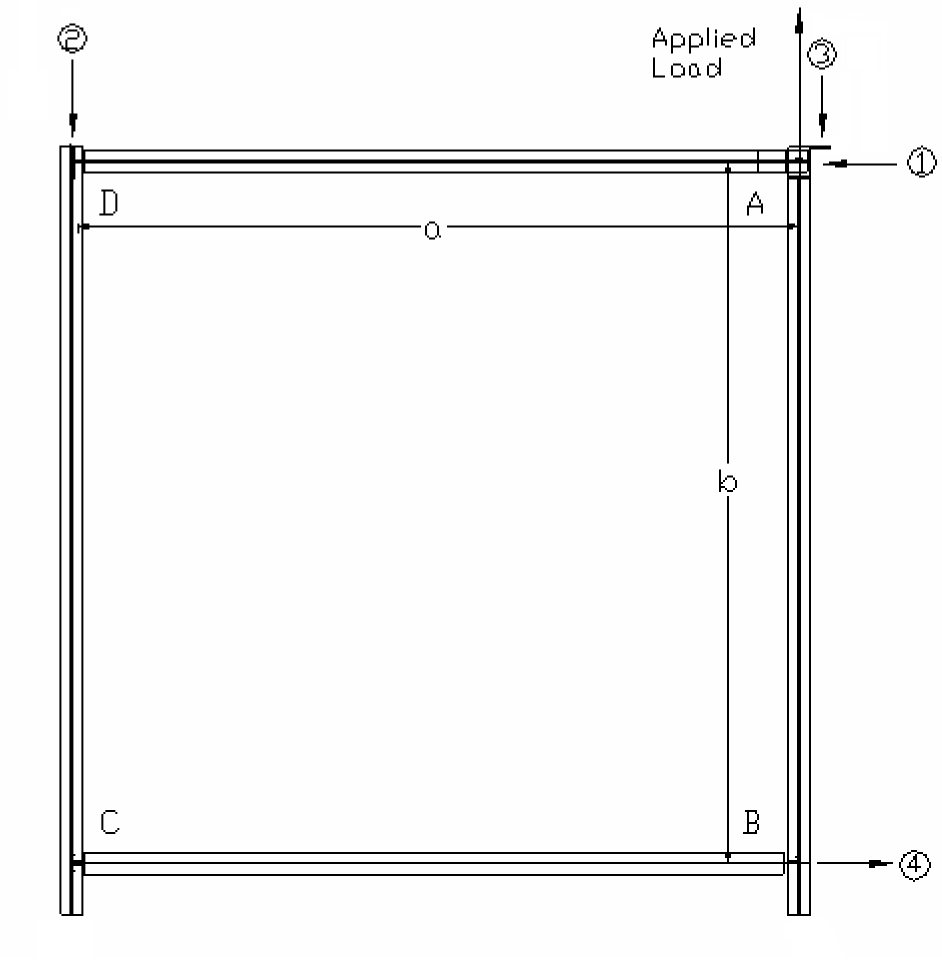

**Figure 3.7. Displacement Transducer Locations (*after Piotter and Esterling, 2001*)**

In accordance with the "Cantilever Test Method for Cold-Formed Steel Diaphragms," transverse and parallel deflections were combined to arrive at a net shear and corrected deflection that accounts for movement of the frame supports. Corrected deflection, $\Delta_f$, was computed by:

$$\Delta_f = \Delta_3 - [\Delta_2 + (a/b)(\Delta_1 + \Delta_4)] \qquad (3.1)$$

where a and b are the dimensions of the diaphragm (16 ft and 15 ft respectively) given in Fig. 3.1.

The diaphragm was initially loaded to between 10 and 20 percent of the maximum load and then unloaded. The diaphragm was then loaded to failure in 300 to 500 lb increments. After each increment, the system was allowed to settle and the load and four deflections then recorded. System failure was defined as a significant drop in the measured load vs. displacement curve.

### 3.2.5. Coupon Tests

Tensile coupon tests were conducted on specimens from each type of deck, purlin, and eave strut received. Each specimen's dimensions and loads at failure are reported in Table B1. The specimens were thoroughly cleaned of paint before the thickness was measured. The tension tests were conducted using a 30 kip load cell in an INSTRON Model 4206-006 screw operated testing machine. Tests were preformed at a speed of 0.025 to 0.5 in./min until failure. A summary of the tensile coupon test results is given in Table 3.1.

**Table 3.1. Coupon Test Results**

| Gage | Material Type | Avg Fy (ksi) | Avg Fu (ksi) |
|---|---|---|---|
| 12 | Purlin | 67.3 | 77.2 |
| 12 | Eve Strut | 62.3 | 70.7 |
| 14 | Eve Strut | 68.7 | 76.9 |
| 16 | Purlin | 62.0 | 70.9 |
| 26 | 5'-2" Deck | 107.2 | 110.7 |
| 26 | 10'-4" Deck | 111.1 | 116.0 |

### 3.3. Test Results

A plot of applied load vs. corrected deflection (Equation 3.1) for each series is shown in Figs. 3.8 and 3.9, while the actual measurements can be seen in Tables B1 through B8. The results from the tests are summarized in Tables 3.2 and 3.3. Values are for the diaphragm shear strength calculated using Equation 3.2, which is given in the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms." The maximum diaphragm shear strength, $S_n$, was calculated as follows:

$$S_n = \frac{P_n}{b} \qquad (3.2)$$

where $P_n$ is the maximum applied force and b = 15 ft. The shear stiffness, G, was calculated for each test as follows:

$$G = \left[\frac{P}{\Delta}\right]_{0.4P\max}\left(\frac{a}{b}\right) \qquad (3.3)$$

where $P = 0.4P_{max}$, $\Delta$ = corrected displacement at P, a = 16 ft, and b = 15 ft.

Different failure mechanisms were observed for each series of diaphragm tests. In the 26x12 series, bearing failures occurred in the deck once the maximum load was achieved. This type of failure can be seen in Figs. 3.10 and 3.11. In the 26x16 series, a combination of failures occurred. Once again bearing failure took place, but many screws also exhibited a pull-out failure.

**Table 3.2. 26x12 Series Test Results**

| Insulation Thickness (in) | $P_{max}$ (kips) | $S_n$ (kips/ft) | $0.4P_{max}$ (kips) | $\Delta_{0.4Pmax}$ (in) | G (kips/in) |
|---|---|---|---|---|---|
| **0** | 6.72 | 0.45 | 2.69 | 0.63 | 4.55 |
| **3** | 6.72 | 0.45 | 2.69 | 0.71 | 4.02 |
| **4** | 6.40 | 0.43 | 2.56 | 0.73 | 3.76 |
| **6** | 6.03 | 0.40 | 2.41 | 0.68 | 3.79 |

Notes:

$P_{max}$ = maximum load achieved

$S_n$ = maximum shear strength

$\Delta_{0.4Pmax}$ = corrected displacement at $0.4P_{max}$

G = diaphragm shear stiffness

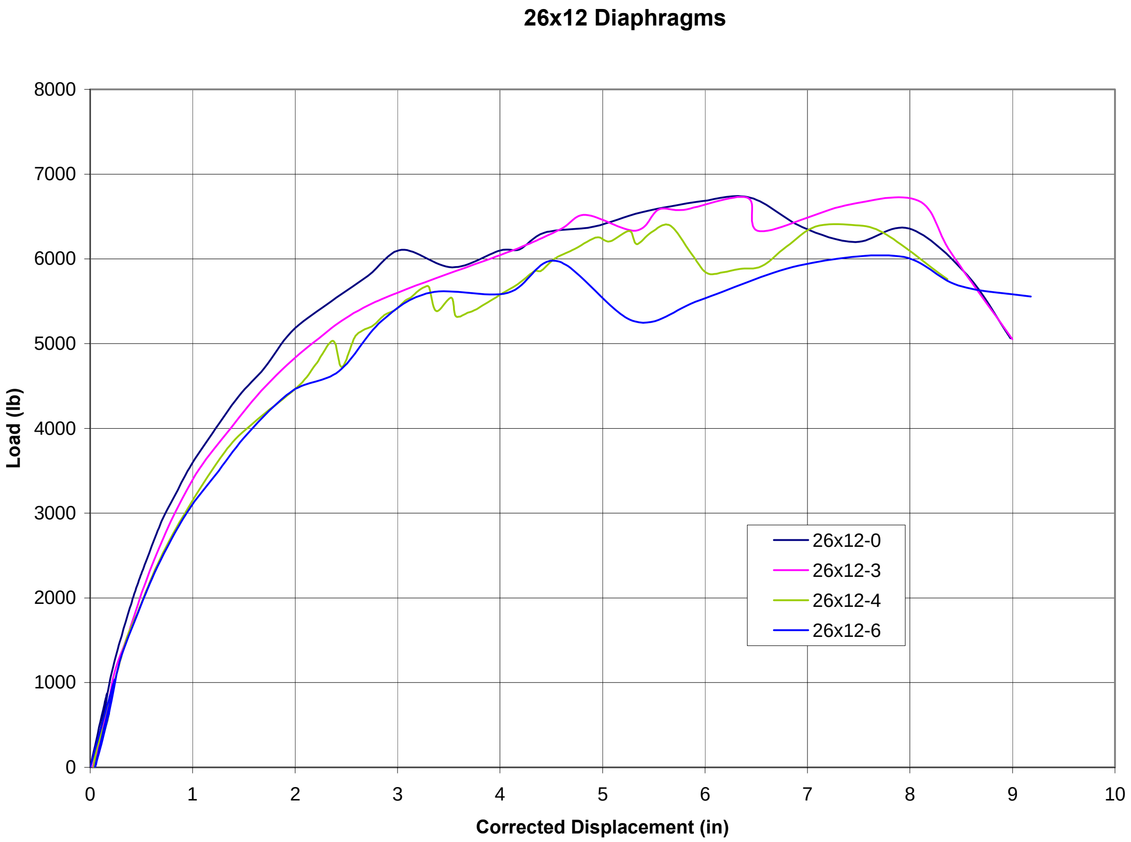

**Figure 3.8. Load vs. Adjusted Deflection for 26x12 Series**

**Table 3.3. 26x16 Series Test Results**

| Insulation Thickness (in) | $P_{max}$ (kips) | $S_n$ (kips/ft) | $0.4P_{max}$ (kips) | $\Delta_{0.4Pmax}$ (in) | G (kips/in) |
|---|---|---|---|---|---|
| **0** | 4.76 | 0.32 | 1.90 | 1.15 | 1.77 |
| **3** | 4.30 | 0.29 | 1.72 | 0.84 | 2.18 |
| **4** | 4.37 | 0.29 | 1.75 | 0.91 | 2.05 |
| **6** | 4.72 | 0.31 | 1.89 | 1.18 | 1.71 |

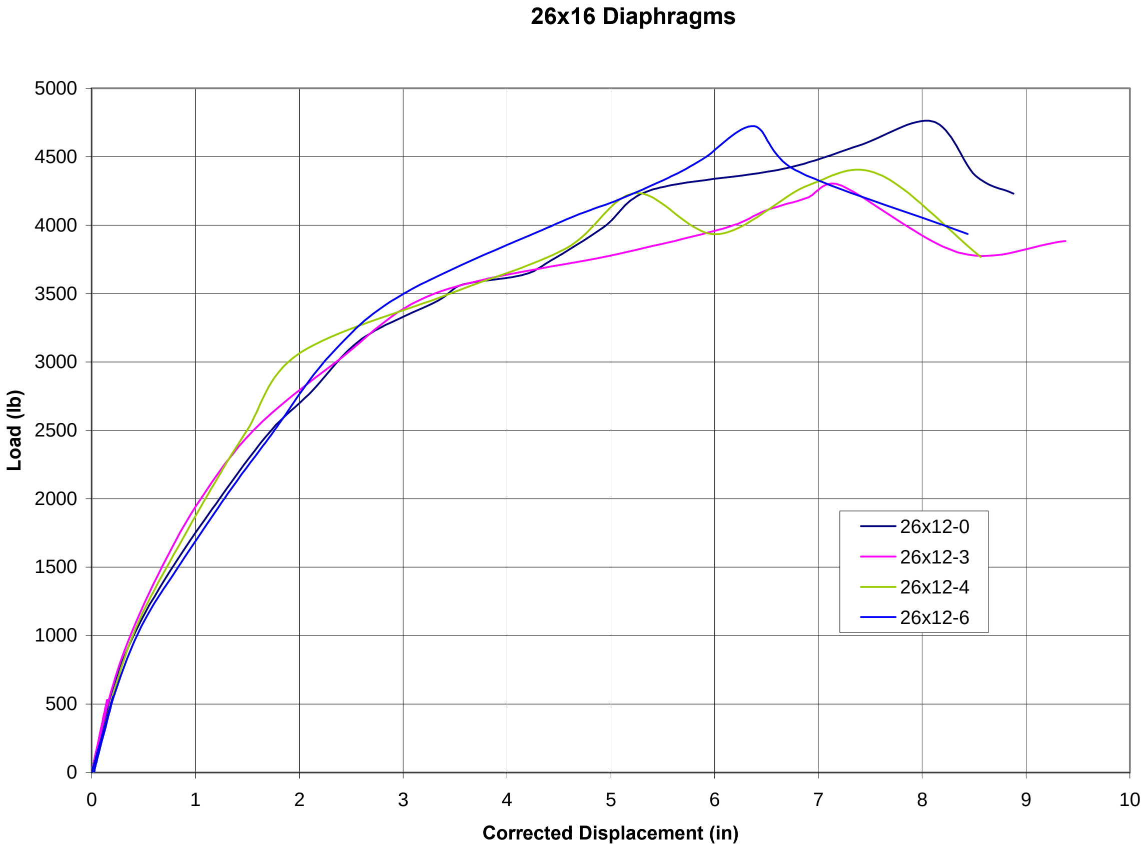

Figure 3.9. Load vs. Adjusted Deflection for 26x16 Series

Figure 3.10. Bearing Failure in Deck

Figure 3.11. Bearing Failure in Deck

### 3.4. Summary

Screw connected cantilever diaphragm tests were conducted in accordance with the AISI "Cantilever Test Method for Cold-Formed Steel Diaphragms" to determine if various thicknesses of insulation affects the diaphragm shear strength. Two series of diaphragm tests, each with four tests where a different thickness of insulation was used for each test, were performed. Test results are presented in Tables 3.2 and 3.3 and Figs. 3.8 and 3.9. Tensile coupon tests were conducted to determine material properties with the results presented in Table 3.1.

### 3.5. Limitations

The results presented in Tables 3.2 and 3.3 represent the shear strength of the system as tested. The results may need to be adjusted to represent actual perimeter and connection configurations found in specific systems.

# Chapter 4

# Data Analysis and Comparison to Proposed Models

## 4.1 Overview

In this chapter, the results from the elemental and diaphragm tests discussed earlier will be examined to determine if modifications to the North American Specification and the Diaphragm Design Manual are necessary to account for the presence of insulation.

## 4.2 Elemental Tests

### 4.2.1 Shear Tests

### 4.2.1.1 Data Analysis

All elemental shear tests were compared to Equations E4.3.1-1 through E.4.3.1-5 of the North American Specification (2001). These equations can be viewed in Section 1.2 of this report and again below:

For $t_2 / t_1 \leq 1.0$, $P_{ns}$ shall be taken as the smallest of

$$P_{ns} = 4.2(t_2^3 d)^{1/2} F_{u2} \quad (4.1)$$

$$P_{ns} = 2.7\, t_1 d\, F_{u1} \quad (4.2)$$

$$P_{ns} = 2.7\, t_2 d\, F_{u2} \quad (4.3)$$

For $t_2 / t_1 \geq 2.5$, $P_{ns}$ shall be taken as the smallest of

$$P_{ns} = 2.7\, t_1 d\, F_{u1} \quad (4.4)$$

$$P_{ns} = 2.7\, t_2 d\, F_{u2} \quad (4.5)$$

For $1.0 < t_2 / t_1 < 2.5$, $P_{ns}$ shall be determined by linear interpolation between the above two cases.

Comparisons to Section E4.3 of the North American Specification (2001) can be viewed in Tables C1 through C7. These tables present the thickness of each plate and strength, the screw diameter, the insulation thickness, and the ratio of plate thicknesses. This information was used with the appropriate AISI Equations and the calculated values were then compared to the test strengths.

There are two definite trends that appear from observing the data. First, there is a decrease in strength with an increase in insulation thickness. Second, as $t_2$ (base thickness) increases, there is an increase in strength. These trends can be seen in Figs. 4.1 and 4.2, respectively. The ratio of the test mean to the calculated mean for all elemental tests using unfaced insulation was 1.00, while the standard deviation was 0.14.

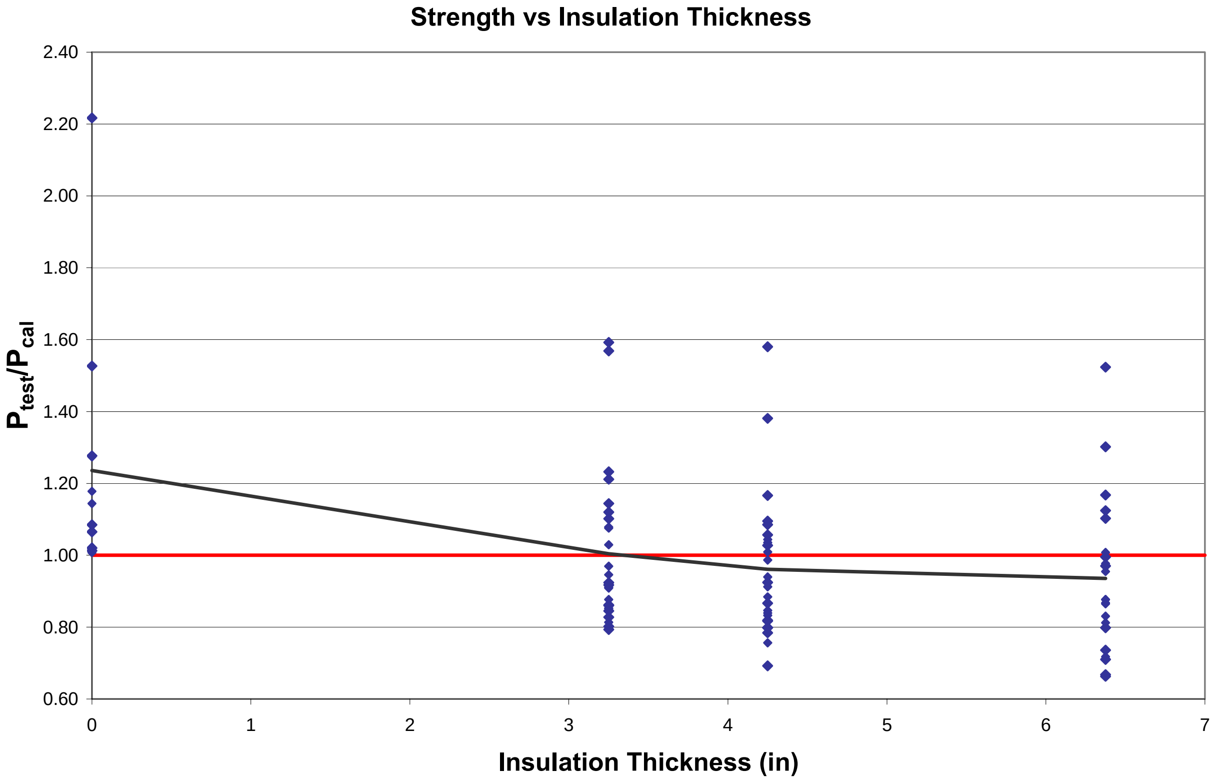

**Figure 4.1 Strength vs Insulation Thickness**

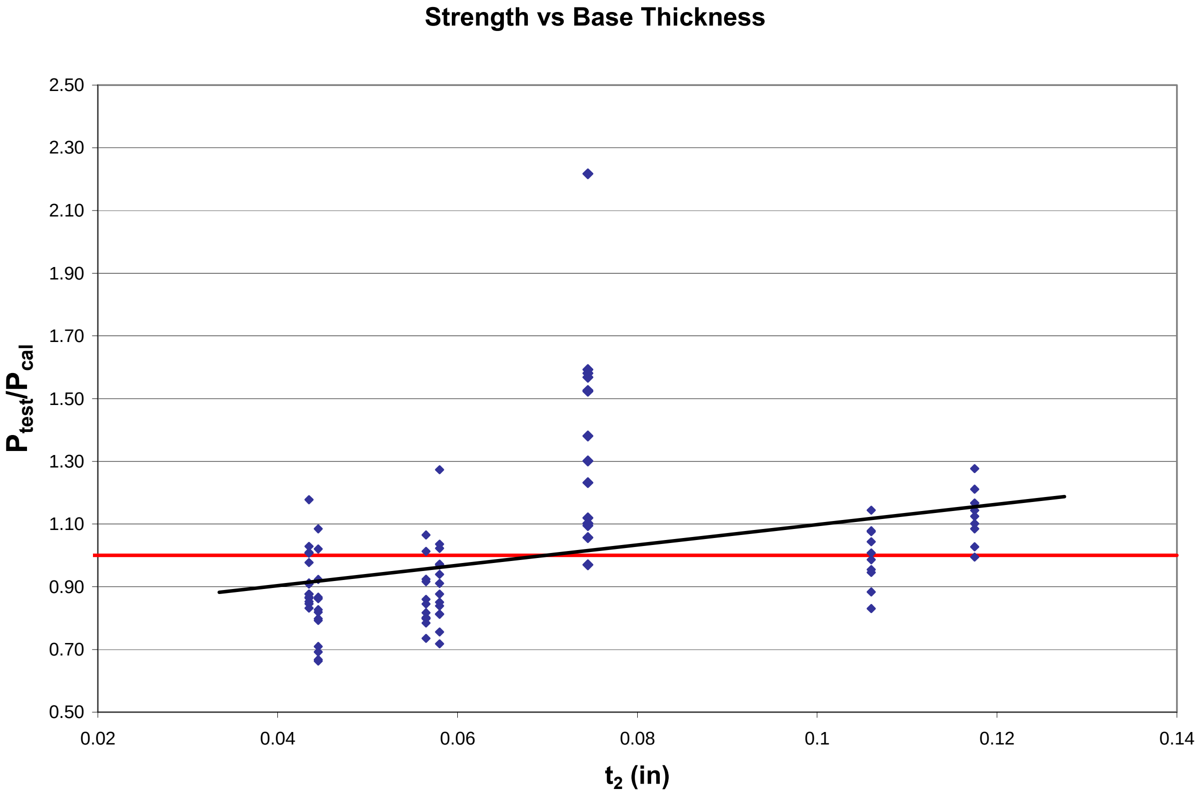

**Figure 4.2 Strength vs $t_2$**

The results from the element tests using faced insulation and the comparison to the same test configurations with similar gaps using unfaced insulation and the North American Specification (2001) can be viewed in Table 4.1. The ratio of $P_{faced}$ to $P_{unfaced}$ in this table shows that the presence of vinyl facing does not cause a reduction in strength from tests using unfaced insulation. The ratio of the test mean to the calculated mean for the 22x18 series using 3 in. insulation and #12 and 14 screws was 0.85 and 0.88, while the standard deviation was 0.112 and 0.052, respectively. The ratio of the test mean to the calculated mean for the 16x16 series and 24x16 series using 6 in. insulation and #14 screws was 0.86 and 0.88, while the standard deviation was 0.112 and 0.113, respectively.

**Table 4.1. Comparison of Elemental Tests Using Vinyl Faced Insulation**

| $t_1$ | $t_2$ | Screw | Faced | Gap (in) | Strength per screw (kips) | Ratio $P_{faced}$ to $P_{unfaced}$ | Ratio $P_{faced}$ to $P_{cal}$ |
|---|---|---|---|---|---|---|---|
| 0.0295 | 0.0435 | # 12 | No | 0.093 | 0.722 | **1.00** | **0.85** |
| 0.0295 | 0.0435 | # 12 | Yes | 0.089 | 0.725 | | |
| 0.0295 | 0.0435 | # 14 | No | 0.093 | 0.845 | **0.97** | **0.88** |
| 0.0295 | 0.0435 | # 14 | Yes | 0.089 | 0.818 | | |
| 0.0565 | 0.0565 | # 14 | No | 0.153 | 0.968 | **1.08** | **0.86** |
| 0.0565 | 0.0565 | # 14 | Yes | 0.141 | 1.046 | | |
| 0.0230 | 0.0580 | # 14 | No | 0.153 | 0.735 | **1.22** | **0.88** |
| 0.0230 | 0.0580 | # 14 | Yes | 0.141 | 0.897 | | |

### 4.2.1.2 Proposed Modifications

Because the elemental tests involving insulation showed a decrease in strength from those tests not involving insulation, two modifications to Equations E4.3.1-1 through E.4.3.1-5 of the North American Specification for the Design of Cold-Formed Steel Members (2001) were considered. The first was to reduce the strength of all screw connections including insulation by multiplying the value obtained from Equations E4.3.1-1 through E.4.3.1-5 by a single value. The second was to multiply the value obtained by an equation involving the compressed insulation thickness or gap distance created by the insulation and the thickness of $t_2$.

In each case, it was assumed that no modification was needed for the samples using nominal 12 and 14 ga material for $t_2$. The reason for this assumption can be seen in Fig. 4.3, which shows all elemental tests involving nominal 12 and 14 ga material. It can be seen that the strengths of the samples in this figure exceeded the predicted strength in all but a few cases. The average of the ratio of the test means to the calculated means for those tests including 12 and 14 ga material was 1.19, while the standard deviation was 0.27.

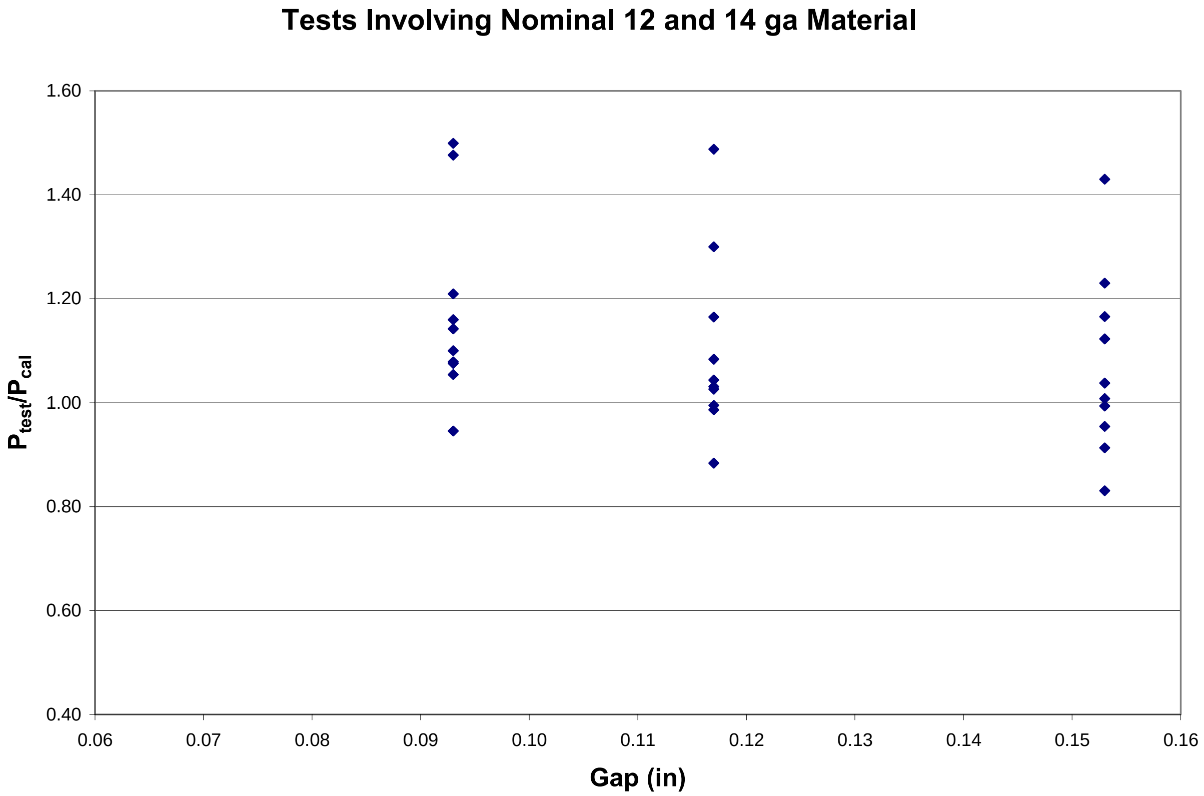

**Figure 4.3. Element Tests Using Nominal 12 and 14 ga Material**

Two proposes were considered for modification to Equations E4.3.1-1 through E.4.3.1-5 of the North American Specification (2001). The first proposal was based on the average ratio of $P_{test}$ to $P_{cal}$, while the second was developed through trial and error. The proposals to be multiplied to AISI Equations E4.3.1-1 through E.4.3.1-5 are as follows:

1) 0.85

2) $1-\dfrac{Gap}{15\,t_2}$

where:

Gap = thickness of the compressed insulation, in.

$t_2$ = thickness of member not in contact with screw head, in.

The two proposals were related to each other by comparing the ratio of the test value to the predicted value including the proposed modifications. Only those tests including insulation and material less then nominal 14 gauge were considered. The results can be viewed in Table 4.2.

**Table 4.2. Comparison of Proposed Modifications Excluding 12 and 14 ga Tests**

| | Current Method | Proposal #1 | Proposal #2 |
|---|---|---|---|
| | $P_{test}/P_{cal}$ | $P_{test}/0.85P_{cal}$ | $P_{test}/(1\text{-}Gap/15\ t_2)P_{cal}$ |
| **Average** | 0.85 | 1.00 | 1.01 |
| **Standard Deviation** | 0.09 | 0.11 | 0.11 |

It can be seen from Table 4.2 that proposal #1 and proposal #2 give approximately the same results with proposal #1 more accurately giving a ratio of the test to predicted values of 1.00. With the standard deviation of each proposal being 0.11, either proposal could be applied to predict a more accurate shear strength, however proposal #1 is slightly more accurate and is easier to apply than proposal #2.

### 4.2.1.3. Resistance Factor Analysis

A resistance factor analysis of the elemental screw shear data and the proposed model was conducted. Resistance factors and factors of safety for four cases were calculated using the same method as used by Pekoz (1990) in his report, which is similar to the method presented in Chapter F of the North American Specification. The equations for the resistance factors and factors of safety can be viewed below in Equations 4.6 and 4.7.

$$\phi = C_\phi M_m F_m P_m e^{-\beta_o \sqrt{V_M^2 + V_F^2 + V_P^2 + V_Q^2}} \qquad (4.6)$$

$$\Omega = 1.6/\phi \qquad (4.7)$$

where:

$\phi$ = resistance factor

$C_\phi$ = calibration coefficient, 1.52

$M_m$ = mean value of material factor, 1.1

$F_m$ = mean value of fabrication factor, 1.0

$P_m$ = mean value of professional factor for tested component

$\beta_o$ = target reliability index, 3.5

$V_M$ = coefficient of variation of material factor, 0.1

$V_F$ = coefficient of variation of fabrication factor, 0.1

$V_P$ = coefficient of variation of test results

$V_Q$ = coefficient of variation of load effect, 0.21

$e$ = natural logarithmic base

$\Omega$ = factor of safety

The results of the calculations for the four chosen cases can be viewed in Table 4.3. All of the resistance factors for the elemental tests were above the value recommended in the North American Specification (2001) of 0.5 and well within the range of resistance factors from the sources given by Pekoz (1990) in his report. This report was fundamental in the development of the current provisions, and included test data with a spread of resistance factors from 0.408 to 0.771.

**Table 4.3. Resistance Factors and Factors of Safety**

| | | Ø | Ω |
|---|---|---|---|
| **All Elemental Tests:** | **No Modification** | 0.670 | 2.39 |
| | **0.85 Modification** | 0.737 | 2.17 |
| **No 12 or 14 gauge Tests:** | **No Modification** | 0.606 | 2.64 |
| | **0.85 Modification** | 0.715 | 2.24 |

### 4.2.2. Tension Tests

All tension tests were compared to Section E4.4 of the North American Specification for the Design of Cold-Formed Steel Members (2001), which states that the tensile strength per screw shall be determined as the smallest of the pull-out and pull-over strength. The equations for these two limit states are:

$$P_{not} = 0.85\ t_c\ d\ F_{u2} \tag{4.8}$$

$$P_{nov} = 1.5\ t_1\ d_w\ F_{u1} \tag{4.9}$$

where:

$d$ = screw diameter

$d_w$ = larger of screw head diameter or washer diameter but not to exceed ½ in.

$F_{u1}$ = tensile strength of member in contact with screw head

$F_{u2}$ = tensile strength of member not in contact with screw head

$t_1$ = thickness of member in contact with screw head

$t_c$ = lesser of depth of penetration and thickness $t_2$

$P_{not}$ = nominal pull-out strength per screw

$P_{nov}$ = nominal pull-over strength per screw

The results from all element tension tests are summarized in Tables 4.4 and 4.5. Each table compares the data obtained during testing to the values calculated from the North American

Specification (2001). While the presence of insulation did lower the tensile strength of the connection, the reduction was not enough for the connection strength to fall below the predicted value. The ratio of the test mean to the calculated mean for the 24x16-10 series using no insulation and 6 3/8 in. insulation was 1.15 and 1.07, while the standard deviation was 0.029 and 0.040, respectively. The ratio of the test mean to the calculated mean for the 22x11-10 series using no insulation and 6 3/8 in. insulation was 1.49 and 1.42, while the standard deviation was 0.055 and 0.032, respectively.

**Table 4.4 24x16-10 Series**

| $t_1$ (in) | $t_2$ (in) | $F_{u1}$ (ksi) | $F_{u2}$ (ksi) | Insulation Thickness (in) | d (in) | dw (in) | $P_{not}$ (kips) | $P_{nov}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ Average |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.023 | 0.0565 | 68.7 | 43.9 | 0 | 0.19 | 0.463 | 0.401 | 1.097 | 0.473 | **1.15** |
| 0.023 | 0.0565 | 68.7 | 43.9 | 0 | 0.19 | 0.463 | 0.401 | 1.097 | 0.454 | |
| 0.023 | 0.0565 | 68.7 | 43.9 | 0 | 0.19 | 0.463 | 0.401 | 1.097 | 0.451 | |
| 0.023 | 0.0565 | 68.7 | 43.9 | 6 3/8 | 0.19 | 0.463 | 0.401 | 1.097 | 0.431 | **1.07** |
| 0.023 | 0.0565 | 68.7 | 43.9 | 6 3/8 | 0.19 | 0.463 | 0.401 | 1.097 | 0.446 | |
| 0.023 | 0.0565 | 68.7 | 43.9 | 6 3/8 | 0.19 | 0.463 | 0.401 | 1.097 | 0.414 | |

**Table 4.5 22x12-10 Series**

| $t_1$ (in) | $t_2$ (in) | $F_{u1}$ (ksi) | $F_{u2}$ (ksi) | Insulation Thickness (in) | d (in) | dw (in) | $P_{not}$ (kips) | $P_{nov}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ Average |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0295 | 0.119 | 49.2 | 54 | 0 | 0.19 | 0.463 | 1.038 | 1.008 | 1.509 | **1.49** |
| 0.0295 | 0.119 | 49.2 | 54 | 0 | 0.19 | 0.463 | 1.038 | 1.008 | 1.610 | |
| 0.0295 | 0.119 | 49.2 | 54 | 0 | 0.19 | 0.463 | 1.038 | 1.008 | 1.517 | |
| 0.0295 | 0.119 | 49.2 | 54 | 6 3/8 | 0.19 | 0.463 | 1.038 | 1.008 | 1.479 | **1.42** |
| 0.0295 | 0.119 | 49.2 | 54 | 6 3/8 | 0.19 | 0.463 | 1.038 | 1.008 | 1.427 | |
| 0.0295 | 0.119 | 49.2 | 54 | 6 3/8 | 0.19 | 0.463 | 1.038 | 1.008 | 1.497 | |

where:

$t_1$ = thickness of member in contact with screw head

$t_2$ = thickness of member not in contact with screw head

$F_{u1}$ = tensile strength of member in contact with screw head

$F_{u2}$ = tensile strength of member not in contact with screw head

d = screw diameter

$d_w$ = larger of screw head diameter or washer diameter

$P_{not}$ = nominal pull-out strength per screw

$P_{nov}$ = nominal pull-over strength per screw

$P_{test}$ = the maximum load recorded during testing

## 4.3. Diaphragm Tests

### 4.3.1. Diaphragm Shear Strength Calculations

The Metal Construction Association (MCA) method outlined in "A Primer on Diaphragm Design" (2004) was used to calculate the predicted shear strength of eight different diaphragm configurations. These configurations correspond to the diaphragms tested in the Virginia Tech Structures Laboratory as presented in Chapter 3. The MCA method for calculating the predicted shear strength of a diaphragm will be outlined in this section. An example calculation of the shear strength of a diaphragm is provided to illustrate the use of the MCA method. The strength of eight different diaphragm configurations was calculated in accordance with the MCA method, which will be presented and compared to the observed tests results.

#### 4.3.1.1. Outline of MCA Procedure

Calculation of the shear strength of a diaphragm involves the consideration of many variables, especially the strength limitations of the connecting devices or fasteners. The MCA method breaks the diaphragm into individual panels and evaluates the strength of each panel.

Each line of panels parallel to the exerted forced is then added together to determine the ultimate strength of the diaphragm. To better illustrate the development of the design equations and variables involved, Figure 4.4 is provided to show in detail the forces involved in the diaphragm.

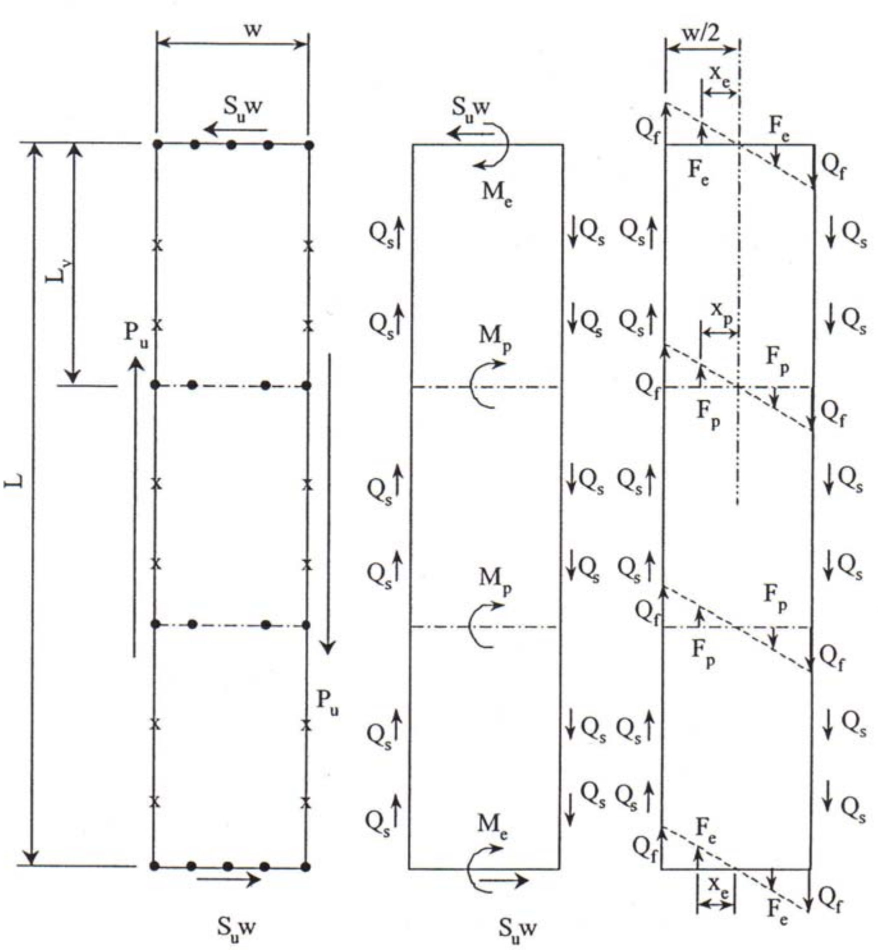

**Figure 4.4. Shear Forces at Fastener Locations (*Luttrell and Mattingly,* 2004)**

The MCA method provides two procedures for determining the strength of the diaphragm. The first procedure uses Equations 4.3 and 4.4, which is based on the interaction of the panel and its fasteners and on the shear strength of the panel corners, respectively. The panel strength is taken to be the lesser value obtained from Equations 4.10 and 4.11. The second procedure uses Equation 4.12, which is based on the edge conditions of the diaphragm. The diaphragm strength is taken to be the lesser of the two procedures.

$$S_u = \{2A(\lambda - 1) + B\}\frac{Q_f}{L} \tag{4.10}$$

$$S_u = Q_f \{\frac{N^2 B^2}{L^2 N^2 + B^2}\}^{0.5} \tag{4.11}$$

$$S_u = (2\alpha_e + n_p \alpha_p + n_e)\frac{Q_f}{L} \tag{4.12}$$

where:

$$B = n_s \alpha_s + 2n_p \sum \alpha_p^2 + 4\sum \alpha_e^2 \tag{4.13}$$

and

$\alpha_e = x_e/w$

$\alpha_p = x_p/w$

$\alpha_s = Q_s/Q_f$

d = fastener diameter, in.

$d_d$ = panel depth, in

L = panel length, ft.

$\lambda = 1 - d_d L_v/(240\ t^{1/2}) \geq 0.7$, corner fastener strength reduction factor

$L_v$ = purlin spacing, ft

N = average number of structural connectors through the bottom flats per unit width at panel end, fasteners/ft

$n_p$ = number of interior purlins per panel length

$n_s$ = number of stitch connections per panel length

$Q_f$ = structural connector shear strength, kips

$Q_s$ = 115(dt), stitch connector shear strength, kips

t = panel base metal thickness, in.

w = panel width, in.

$x_e$ = end of panel fattener position relative to panel center line, in.

$x_p$ = purlin fastener position relative to panel center line, in.

A = 1 for single fastener at panel edges
2 for double edge fasteners

To account for insulation, the MCA method introduces an insulation coefficient, $I_{nf}$, that is used in the calculation of $\alpha_e$ and $\alpha_p$. The insulation coefficient is equal to 0 or 1 depending on whether there is or is not insulation present in the system, respectively. The reason for this is because insulation introduces eccentricity into the structural connections so that the connections cannot be fully developed. Therefore, the MCA method assumes that shear forces can only be transferred by the diaphragm at the sidelaps of the panels and any contribution made by those structural connections with insulation is neglected. In the eight diaphragm tests conducted, the panel-to-panel stitch connectors were installed as shown in Fig. 4.5. This resulted in $\alpha_e$ and $\alpha_p$ being equal to 0 in the six diaphragm tests involving insulation. This approach is very conservative because the structural fasteners, while not being fully developed, still contribute to the diaphragm strength.

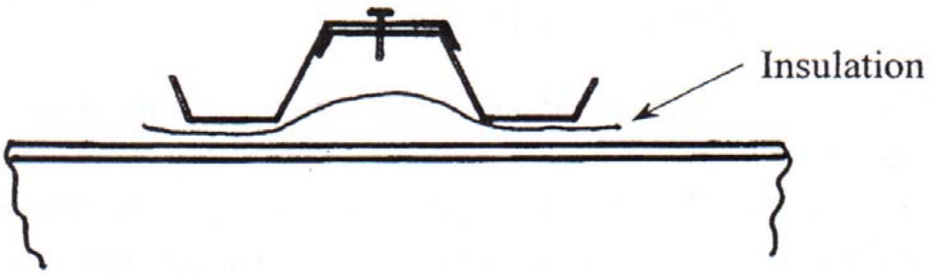

**Figure 4.5. Stitch Screw Installation (*after Luttrell and Mattingly,* 2004)**

#### 4.3.1.2. Connection Strength

An accurate method of predicting the strength of the connections is essential for the accurate prediction of the overall diaphragm strength. Structural and stitch (sidelap) connections are the two types of connections used on a diaphragm. A fastener used to connect one or more sheets to a heavier frame or structural member is considered a structural connection. A stitch or sidelap connection is used to fasten two adjacent panels together without connecting them to a heavier frame or structural member.

The MCA method uses equations for calculating the strength of the structural connections from the Diaphragm Design Manual (Luttrell 2004) and the North American Specification (2001), where the lowest value is taken to be $Q_f$. The equation developed by Luttrell (Equation 4.14) requires that the framing be sufficiently thick so that the frame does not control shear, which is the case in most situations. When the frame is thin, the shear strength equations presented in the North American Specification for the frame must also be considered. These are the same equations presented in Section 1.2 of this report, with the exception that only the frame is considered. The AISI equations used in the MCA procedure are presented in Equations 4.15 through 4.17. The equation taken from the Diaphragm Design Manual (Luttrell 2004) is as follows:

$$Q_f = 1.25F_yt(1\text{-}0.005F_y) \leq 60 \text{ ksi} \quad (4.14)$$

where:

$F_y$ = yield strength of the panel, ksi.

t = panel thickness, in.

The equations taken from the North American Specification (2001) are as follows:

For $t_s / t \leq 1.0$, $Q_f$ shall be taken as the smallest of

$$Q_f = 4.2(t_s^3d)^{1/2}F_{us} \quad (4.15)$$

$$Q_f = 2.7\ t_sd\ F_{us} \quad (4.16)$$

For $t_s / t \geq 2.5$

$$Q_f = 2.7\ t_sd\ F_{us} \quad (4.17)$$

For $1.0 < t_s / t < 2.5$, $Q_f$ shall be determined by linear interpolation between the above two cases.

where:

d = nominal screw diameter

$t_s$ = thickness of the frame (member not in contact with screw head)

$F_{us}$ = tensile strength of the frame

The shear strength of the stitch connectors is calculated using an equation presented in the Diaphragm Design Manual (Luttrell 2004). The stitch screws are not anchored into thicker and more rigid elements and therefore tip over more easily than a structural connection. Studies concluded that the stitch screw's strength is calculated using Equation 4.18.

$$Q_s = 115\ dt \quad (4.18)$$

When the connected panel thickness is less than 0.028 inches, studies have shown that the values of $Q_f$ and $Q_s$ should be multiplied by the factor:

$$(t/0.028)^{1/2}$$

### 4.3.1.3. Example Calculations

The following example demonstrates the procedure for calculating the strength of a particular diaphragm configuration. The configuration is for the 26x12-0 and the 26x16-0 test setups. The test configurations label was defined in Section 3.2.1 of this report.

The following procedure is for a 3 ft, 2 span panel without insulation. The following variables are defined for Equations 4.10 and 4.11.

$\alpha_e = 2(3.5+8.5+15.5)/36 = 1.528$

$\alpha_p = (3.5+8.5+15.5)/36 = 0.764$

$\alpha_e^2 = 2(3.5^2+8.5^2+15.5^2)/36^2 = 0.501$

$\alpha_p^2 = (3.5^2+8.5^2+15.5^2)/36^2 = 0.251$

$A = 1$

$d_d = 1.25$ in.

$L = 10$ ft

$L_v = 5$ ft

$n_p = 1$

$n_s = 7$

$t = 0.018$ in.

$$\lambda = 1 - \frac{d_d L_v}{240\sqrt{t}} = 1 - \frac{1.25(5)}{240\sqrt{0.018}} = 0.806$$

$$Q_f = 1.25F_y t(1-0.005F_y)(\frac{t}{0.028})^{1/2} = 1.25(116)(0.018)(1-0.005(116))(\frac{0.018}{0.028})^{1/2}$$
$$= 0.879\ kips$$

$Q_s = 24.3\ t\ (t/0.028)^{1/2} = 24.3(0.018)(0.018/0.028)^{1/2} = 0.351\ kips$

$\alpha_s = Q_s/Q_f = 0.351/0.879 = 0.399$

N = 2 fasteners per foot

Solving Equation 4.13:

$$B = n_s\alpha_s + 2n_p\alpha_p^2 + 4\alpha_e^2 = 7(0.399) + 2(1)(0.251) + 4(0.501) = 5.299 \qquad (4.13)$$

Solving Equation 4.10:

$$S_u = \{2A(\lambda-1)+B\}\frac{Q_f}{L} = \{2(1)(0.806-1)+5.299\}\frac{0.879}{10} = 0.432\ kpf \leftarrow \text{Use} \qquad (4.10)$$

Solving Equation 4.11:

$$S_u = Q_f\ \{\frac{N^2B^2}{L^2N^2+B^2}\}^{0.5} = 0.879\{\frac{2^2(5.299)^2}{10^2(2)^2+5.299^2}\}^{0.5} = 0.450\ kpf \qquad (4.11)$$

The following procedure is for a 3 ft, 1 span panel without insulation. The following variables are different from the previous case and are defined for Equations 4.10 and 4.11.

$\alpha_p = \alpha_p^2 = 0$

L = 5 ft

$L_v$ = 5 ft

$n_p = 0$

$n_s = 4$

Solving Equation 4.13:

$$B = n_s\alpha_s + 2n_p\alpha_p^2 + 4\alpha_e^2 = 4(0.399) + 0 + 4(0.501) = 3.600 \qquad (4.13)$$

Solving Equation 4.10:

$$S_u = \{2A(\lambda - 1) + B\}\frac{Q_f}{L} = \{2(1)(0.806 - 1) + 3.600\}\frac{0.879}{5} = 0.565\,kpf \leftarrow \text{Use} \qquad (4.10)$$

Solving Equation 4.11:

$$S_u = Q_f\,\{\frac{N^2B^2}{L^2N^2 + B^2}\}^{0.5} = 0.879\{\frac{2^2(3.600)^2}{5^2(2)^2 + 3.600^2}\}^{0.5} = 0.595\,kpf \qquad (4.11)$$

The following procedure is for a 3 ft panel without insulation. Because the diaphragm was 15 ft long, the strengths of the 2 and 1 span panels, multiplied by their appropriate lengths, must be added together. This is done below to achieve a diaphragm shear strength.

$$P_{ult} = 10(0.432) + 5(0.565) = 7.145\,kips \qquad (4.19)$$

The same procedure must be repeated for insulation and for the 1.5 ft panel with and without insulation. The same setup must also be checked for edge conditions. The results of these calculations can be viewed in Table 4.6.

**Table 4.6. Predicted Diaphragm Strengths**

| Case | Critical Element | $P_{ult}$ (kips) |
|---|---|---|
| 1) No Insulation | 3 foot Panel | 7.15 |
| | 1.5 foot Panel | 5.16 |
| | Edge | 6.05 |
| 2) Insulation | 3 foot Panel | 3.84 |
| | 1.5 foot Panel | 3.84 |
| | Edge | 0 |

It can be seen from Table 4.6 that the MCA method predicts the shear strength of the diaphragm without insulation to be controlled by 1.5 ft panels and to have a total strength of 5.16

kips. The same method also predicts the shear strength of the diaphragm with insulation to be controlled by edge conditions and predicts a strength of 0 kips for this case. The method is clearly wrong in its prediction of the second case so the critical element will be assumed to be the 3 ft and 1.5 ft panels, which both predict a shear strength of 3.84 kips. Even with this assumption, the second case predicts a very conservative reduction in strength of 25%.

For the diaphragm tests without insulation, the MCA method predicted failure to occur in the 1.5 ft panel, but this is not what was observed. While there was significant deformation in the 1.5 ft panel, the diaphragm's failure occurred in the 3 ft panel directly in line with the applied force.

### 4.3.2. Comparison of Calculated Strength to Observed Strength

The predicted and observed diaphragm strengths are compared in Table 4.7. The predicted strengths were calculated using the MCA method and also by using the proposed modifications for insulation to the North American Specification to determine $Q_f$ and then proceeding as before with the MCA method.

**Table 4.7 Predicted and Observed Diaphragm Test Results**

| Test | Predicted Results Using The MCA Method (kips) | Predicted Results Using Proposed AISI Modification For Insulation (kips) | Observed Results (kips) |
|---|---|---|---|
| 26x12-0 | 5.16 | --- | 6.72 |
| 26x12-3 | 3.84 | 3.84 | 6.72 |
| 26x12-4 | 3.84 | 3.84 | 6.40 |
| 26x12-6 | 3.84 | 3.84 | 6.03 |
| 26x16-0 | 5.16 | --- | 4.76 |
| 26x16-3 | 3.84 | 3.84 | 4.30 |
| 26x16-4 | 3.84 | 3.84 | 4.37 |
| 26x16-6 | 3.84 | 3.84 | 4.72 |

The observed results for the 26x12 series are all greater than the predicted results. It can be seen that the presence of insulation does appear to cause a reduction in the shear strength of the diaphragm, but not nearly as much as predicted by the MCA method or the proposed modification to the North American Specification. When taken as a whole, the 26x12 series has a test mean of 6.47 kips and a standard deviation of 0.328.

The observed results for the 26x16 series are more mixed when compared to the predicted results. The strength of the observed test without insulation is below the predicted, while the tests including insulation are all above the values predicted by the MCA method and the proposed modification to the North American Specification. It can be seen again that presence of insulation does appear to cause a reduction in the shear strength of the diaphragm, but not as much as predicted by the MCA method or the proposed modification to the North American Specification. When taken as a whole, the 26x12 series has a test mean of 4.54 kips and a standard deviation of 0.236.

Comparing the MCA method to the observed test results shows that there are significant differences between the two values for each test. Therefore, it is clear that the presence of insulation does not affect the shear strength as much as predicted.

## 4.4. Summary

In this chapter, all elemental tests were compared to the appropriate section of the North American Specification for the Design of Cold-Formed Steel Members (2001). The tests using faced fiberglass insulation were also compared to similar tests using unfaced insulation to determine if the vinyl facing has any effect on the shear strength of screw connections. The results from the shear tests using faced and unfaced fiberglass insulation, with the exception of the tests using nominal 12 and 14 ga material, were found to be below the predicted value from the North American Specification (2001) in most cases. The tests involving vinyl faced insulation showed that vinyl facing has little to no effect on the shear strength of screw connections, while the two sets of elemental tension tests determined that insulation has little to no effect on the tensile strength of screw connections.

Two modifications were proposed to compensate for the reduction in the strength. It was found that multiplying the predicted shear strength by 0.85 more accurately predicts the shear strength of the connection. However, when the element shear tests using unfaced insulation were compared the sources used by Pekoz (1990) to derive the current specifications, the tests involving insulation were found to be within the spread of those sources.

All diaphragm tests were compared to the Metal Construction Association (MCA) method outlined in "A Primer on Diaphragm Design" (Luttrell and Mattingly 2004). Predicted values were calculated using the MCA method and also by using the proposed modifications to the North American Specification to determine $Q_f$ and then proceeding as before with the MCA method. The observed results showed that insulation does appear to reduce the shear strength of the diaphragm and that the proposed modification to the North American Specification does not predict the shear strength of the diaphragm more accurately than strictly using the MCA method.

# Chapter 5

# Conclusions and Recommendations

## 5.1. Conclusions

From the results of the 435 elemental tests using unfaced insulation, it can be concluded that the presence of insulation between two steel sheets connected by screws reduces the shear strength of the connection. It can also be observed that the strength of the connections involving insulation, with the exception of the tests using nominal 12 and 14 ga material, is less than the strength predicted by the North American Specification (2001) in most cases. By applying a simple multiplier of 0.85 to the shear strength obtained from Section E4 of the North American Specification (2001), the predicted shear strength more closely follows the trend of the actual strength. However, reviewing the reliability analysis of the elemental tests shows that the resistance factors calculated fall well within the range of the resistance factors of the past research used to develop Section E4.3 of North American Specification.

From the results of the eight diaphragm tests, it can be concluded that the presence of insulation does reduce the shear strength of the diaphragm. It can also be seen that the proposed modification to the North American Specification does not predict the shear strength of the diaphragm any more accurately than strictly using the MCA method.

By observing the data obtained from the elemental and diaphragm tests, it appears that a modification to Section E4.3 of the North American Specification is clearly needed. However, when the data acquired from this study and the screw shear data obtained in past research are combined, it is difficult to distinguish the past and present research. The shear strength of the tests involving insulation fit well within the scatter of the past screw shear tests excluding insulation.

## 5.2. Recommendations

While the presence of insulation between two steel sheets connected by screws reduces the shear strength of the connection, the current equations for predicting this strength in Section E4.3 of the North American Specification (2001) are adequate. A resistance factor analysis of the elemental tests showed that the resistance factors fell well within the range of the resistance factors of the data used to develop the current equations and were well above the value recommended in the North American Specification of 0.5. The diaphragm tests showed that the proposed modifications were not more accurate than the MCA method. Therefore, it is recommended that no modification be made to account for the presence of up to 6 3/8 in. of uncompressed fiberglass insulation placed between two steel sheets connected by screws.

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# APPENDIX A

# ELEMENT TEST DATA

**Table A1. Coupon Test Results**

| Shipment | Gage | Test # | Thickness (in.) | Width (in.) | Yield Load (kips) | Peak Load (kips) | Avg Fy (ksi) | Avg Fu (ksi) |
|---|---|---|---|---|---|---|---|---|
| **1** | **12** | 1 | 0.106 | 0.497 | NA | 3.856 | **NA** | **73.0** |
| | | 2 | 0.106 | 0.497 | NA | 3.893 | | |
| | | 3 | 0.106 | 0.494 | NA | 3.759 | | |
| **1** | **16** | 1 | 0.058 | 0.492 | NA | 2.224 | **NA** | **77.7** |
| | | 2 | 0.058 | 0.492 | NA | 2.228 | | |
| | | 3 | 0.058 | 0.506 | NA | 2.266 | | |
| **1** | **22** | 1 | 0.031 | 0.496 | NA | 0.944 | **NA** | **62.8** |
| | | 2 | 0.031 | 0.503 | NA | 0.988 | | |
| | | 3 | 0.031 | 0.503 | NA | 0.992 | | |
| **1** | **24** | 1 | 0.023 | 0.501 | NA | 0.790 | **NA** | **68.7** |
| | | 2 | 0.023 | 0.503 | NA | 0.796 | | |
| | | 3 | 0.023 | 0.504 | NA | 0.798 | | |
| **2** | **12** | 1 | 0.117 | 0.500 | 2.50 | 3.189 | **43.9** | **54.7** |
| | | 2 | 0.117 | 0.500 | 2.60 | 3.196 | | |
| | | 3 | 0.117 | 0.500 | 2.60 | 3.212 | | |
| **2** | **18** | 1 | 0.045 | 0.500 | 1.05 | 1.283 | **47.0** | **57.7** |
| | | 2 | 0.045 | 0.500 | 1.05 | 1.290 | | |
| | | 3 | 0.045 | 0.500 | 1.04 | 1.281 | | |
| **3** | **16** | 1 | 0.057 | 0.500 | 0.81 | 1.236 | **28.0** | **43.5** |
| | | 2 | 0.057 | 0.500 | 0.80 | 1.244 | | |
| | | 3 | 0.057 | 0.500 | 0.78 | 1.237 | | |
| **3** | **18** | 1 | 0.044 | 0.500 | 0.68 | 1.072 | **31.4** | **49.2** |
| | | 2 | 0.044 | 0.500 | 0.68 | 1.064 | | |
| | | 3 | 0.044 | 0.500 | 0.69 | 1.074 | | |
| **3** | **22** | 1 | 0.0295 | 0.500 | 0.46 | 0.742 | **30.0** | **49.2** |
| | | 2 | 0.0300 | 0.500 | 0.44 | 0.730 | | |
| | | 3 | 0.0300 | 0.500 | 0.44 | 0.731 | | |
| **4** | **14** | 1 | 0.075 | 0.500 | 1.72 | 2.049 | **46.4** | **55.1** |
| | | 2 | 0.075 | 0.500 | 1.75 | 2.054 | | |
| | | 3 | 0.075 | 0.500 | 1.71 | 2.054 | | |
| **4** | **26** | 1 | 0.019 | 0.500 | 0.56 | 0.580 | **60.2** | **62.5** |
| | | 2 | 0.019 | 0.500 | 0.56 | 0.577 | | |
| | | 3 | 0.019 | 0.500 | 0.55 | 0.577 | | |

### Table A2. Gap Measurements for 3 1/4 in. Unfaced Insulation

| 24-16 Thickness (in) | 22-12 Thickness (in) | 26-14 Thickness (in) |
|---|---|---|
| 0.196 | 0.223 | 0.180 |
| 0.182 | 0.250 | 0.180 |
| 0.185 | 0.211 | 0.183 |
| 0.202 | 0.232 | 0.180 |
| 0.162 | 0.228 | 0.185 |
| 0.169 | 0.228 | 0.184 |
| 0.161 | 0.229 | 0.189 |
| 0.183 | 0.227 | 0.199 |
| 0.146 | 0.221 | 0.187 |
| 0.166 | 0.229 | 0.195 |
| 0.188 | 0.260 | 0.184 |
| 0.178 | 0.243 | 0.183 |
| 0.204 | 0.197 | 0.205 |
| 0.200 | 0.193 | 0.202 |
| 0.161 | 0.223 | 0.200 |
| 0.155 | 0.244 | 0.184 |
| 0.166 | 0.236 | 0.199 |
| 0.159 | 0.270 | 0.201 |
| 0.169 | 0.239 | 0.183 |
| 0.169 | 0.224 | 0.190 |
|  | 0.265 | 0.192 |
|  | 0.215 | 0.190 |
|  |  | 0.178 |
|  |  | 0.181 |
|  |  | 0.182 |
|  |  | 0.193 |
|  |  | 0.185 |
|  |  | 0.185 |
|  |  | 0.187 |
|  |  | 0.179 |
|  |  | 0.184 |
|  |  | 0.194 |
|  |  | 0.188 |
|  |  | 0.176 |
|  |  | 0.180 |
|  |  | 0.190 |
|  |  | 0.160 |
|  |  | 0.165 |

**Table A3. Gap Measurements for 4 1/4 in. Unfaced Insulation**

| 24-16 Thickness (in) | 22-12 Thickness (in) | 26-14 Thickness (in) |
|---:|---:|---:|
| 0.185 | 0.269 | 0.233 |
| 0.186 | 0.275 | 0.208 |
| 0.190 | 0.239 | 0.181 |
| 0.198 | 0.241 | 0.189 |
| 0.208 | 0.236 | 0.228 |
| 0.189 | 0.267 | 0.245 |
| 0.198 | 0.250 | 0.228 |
| 0.196 | 0.225 | 0.212 |
| 0.180 | 0.238 | 0.201 |
| 0.184 | 0.237 | 0.199 |
| 0.197 | 0.257 | 0.205 |
| 0.207 | 0.216 | 0.213 |
| 0.206 | 0.248 | 0.218 |
| 0.196 | 0.246 | 0.212 |
| 0.200 | 0.228 | 0.206 |
| 0.201 | 0.250 | 0.196 |
| 0.197 | 0.217 | 0.188 |
| 0.199 | 0.242 | 0.240 |
| 0.211 | 0.263 | 0.223 |
| 0.204 | 0.248 | 0.239 |
| 0.228 | 0.233 | 0.240 |
| 0.222 | 0.225 | 0.242 |
| 0.210 | 0.245 | 0.221 |
| 0.211 | 0.247 | 0.232 |
| 0.186 | 0.256 | 0.208 |
| 0.192 | 0.255 | 0.220 |
| 0.207 | 0.274 | 0.234 |
| 0.180 | 0.251 | 0.216 |
| 0.198 | 0.261 | 0.235 |
| 0.183 | 0.256 | 0.200 |
|  |  | 0.230 |
|  |  | 0.242 |
|  |  | 0.200 |
|  |  | 0.207 |
|  |  | 0.227 |
|  |  | 0.233 |

## Table A4. Gap Measurements for 6 3/8 in. Unfaced Insulation

| 24-16 Thickness (in) | 22-12 Thickness (in) | 26-14 Thickness (in) |
|---:|---:|---:|
| 0.304 | 0.295 | 0.277 |
| 0.313 | 0.285 | 0.284 |
| 0.244 | 0.311 | 0.276 |
| 0.250 | 0.214 | 0.217 |
| 0.226 | 0.283 | 0.278 |
| 0.212 | 0.260 | 0.285 |
| 0.198 | 0.294 | 0.260 |
| 0.243 | 0.283 | 0.292 |
| 0.264 | 0.279 | 0.278 |
| 0.245 | 0.277 | 0.250 |
| 0.247 | 0.251 | 0.234 |
| 0.237 | 0.279 | 0.215 |
| 0.229 | 0.309 | 0.309 |
| 0.229 | 0.289 | 0.276 |
| 0.237 | 0.250 | 0.209 |
| 0.258 | 0.270 | 0.246 |
| 0.217 | 0.270 | 0.276 |
| 0.198 | 0.257 | 0.262 |
| 0.201 | 0.311 | 0.271 |
| 0.235 | 0.283 | 0.253 |
| 0.250 | 0.270 | 0.198 |
|  | 0.291 | 0.275 |
|  | 0.257 | 0.241 |
|  | 0.314 | 0.323 |
|  | 0.292 | 0.248 |
|  | 0.230 | 0.228 |
|  | 0.267 | 0.224 |
|  | 0.266 | 0.242 |
|  | 0.258 |  |
|  | 0.264 |  |
|  | 0.318 |  |
|  | 0.297 |  |

## Table A5. Gap Measurements for 3 in. Vinyl Faced Insulation

| 22-18 Thickness (in) |
|---|
| 0.160 |
| 0.172 |
| 0.191 |
| 0.169 |
| 0.158 |
| 0.159 |
| 0.141 |
| 0.172 |
| 0.173 |
| 0.135 |

## Table A6. Gap Measurements for 6 in. Vinyl Faced Insulation

| 24-16 Thickness (in) | 16'-16' Thickness (in) |
|---|---|
| 0.232 | 0.267 |
| 0.221 | 0.246 |
| 0.220 | 0.254 |
| 0.223 | 0.241 |
| 0.229 | 0.245 |

## Table A7. Test Matrix for Elemental Shear Tests

|  | $t_1$ (ga) | 18 |  |  |  | 16 |  |  |  | 14 |  |  |  | 12 |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Screw | #8 | #10 | #12 | #14 | #8 | #10 | #12 | #14 | #8 | #10 | #12 | #14 | #8 | #10 | #12 | #14 |
| $t_2$ (ga) | Insulation (in) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 26 | 0 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |  |  |  |  |
|  | 3 1/4 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |  |  |  |  |
|  | 4 1/4 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |  |  |  |  |
|  | 6 3/8 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |  |  |  |  |
| 24 | 0 |  |  |  |  | B 1 | B 2 | B 2 | B 1 |  |  |  |  |  |  |  |  |
|  | 3 1/4 |  |  |  |  |  | B 2 | B 2 | B 2 |  |  |  |  |  |  |  |  |
|  | 4 1/4 |  |  |  |  |  | B 2 | B 2 | B 2 |  |  |  |  |  |  |  |  |
|  | 6 3/8 |  |  |  |  | B 1 | B 2 | B 2 | B 1 |  |  |  |  |  |  |  |  |
| 22 | 0 | B 1 | B 2 | B 2 | B 1 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |
|  | 3 1/4 |  | B 2 | B 2 | B 2 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |
|  | 4 1/4 |  | B 2 | B 2 | B 2 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |
|  | 6 3/8 | B 1 | B 2 | B 2 | B 1 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |
| 18 | 0 | A 1 | A 2 | A 2 | A 1 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |
|  | 3 1/4 |  | A 2 | A 2 | A 2 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |
|  | 4 1/4 |  | A 2 | A 2 | A 2 |  |  |  |  |  |  |  |  |  | C 2 | C 2 | C 2 |
|  | 6 3/8 | A 1 | A 2 | A 2 | A 1 |  |  |  |  |  |  |  |  | C 1 | C 2 | C 2 | C 1 |
| 16 | 0 |  |  |  |  | A 1 | A 2 | A 2 | A 1 |  |  |  |  |  |  |  |  |
|  | 3 1/4 |  |  |  |  |  | A 2 | A 2 | A 2 |  |  |  |  |  |  |  |  |
|  | 4 1/4 |  |  |  |  |  | A 2 | A 2 | A 2 |  |  |  |  |  |  |  |  |
|  | 6 3/8 |  |  |  |  | A 1 | A 2 | A 2 | A 1 |  |  |  |  |  |  |  |  |

**Categories**

|  |  |  |  |  |
|---|---|---|---|---|
| A | $t_1 = t_2$ | 16 -> 16 $t_2 / t_1 = 1.0$ | 18 -> 18 $t_2 / t_1 = 1.0$ |  |
| B | $t_1 < t_2 \leq 2.5\ t_1$ | 22 -> 18 $t_2 / t_1 = 1.5$ | 24 -> 16 $t_2 / t_1 = 2.5$ |  |
| C | $t_2 > 2.5\ t_1$ | 18 -> 12 $t_2 / t_1 = 2.6$ | 22 -> 12 $t_2 / t_1 = 3.4$ | 26 -> 14 $t_2 / t_1 = 4.2$ |

**Matrix Notes**

1) Phase one is meant to test the extremes of the test matrix. Tests (marked as X 1, where X = A, B, or C) will be made with no insulation to confirm the present equations and 6 3/8''' of insulation to test the greatest depth used in construction for two groups in each of the three categories.

2) Upon completion of phase one, further tests (marked as X 2) will be done to give better understanding of the performance of screw connections under shear with the presence of insulation.

3) Some tests may not be completed if the shear strength of the chosen screws is less than the screw strength of the given plates.

## Table A8. Test Results for 26x14 Series

| $t_1$ | $t_2$ | Screw | Insulation (in) | 1 (kips) | 2 (kips) | Test 3 (kips) | 4 (kips) | 5 (kips) | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.019 | 0.075 | # 8 | 0 | 1.692 | 1.647 | 1.575 | 1.559 | 1.641 | 1.623 | 0.811 |
| 0.019 | 0.075 | # 8 | 3 1/4 | 1.227 | 1.137 | 1.159 | 1.152 | 1.153 | 1.166 | 0.583 |
| 0.019 | 0.075 | # 8 | 4 1/4 | 1.140 | 1.130 | 1.158 | 1.252 | 1.104 | 1.157 | 0.578 |
| 0.019 | 0.075 | # 8 | 6 3/8 | 1.084 | 1.141 | 1.093 | 1.147 | 1.111 | 1.115 | 0.558 |
| 0.019 | 0.075 | # 10 | 3 1/4 | 1.099 | 1.466 | 1.461 | 1.352 | 1.272 | 1.330 | 0.665 |
| 0.019 | 0.075 | # 10 | 4 1/4 | 1.165 | 1.232 | 1.244 | 1.243 | 0.970 | 1.171 | 0.585 |
| 0.019 | 0.075 | # 10 | 6 3/8 | 1.130 | 1.116 | 1.100 | 1.119 | 1.053 | 1.104 | 0.552 |
| 0.019 | 0.075 | # 12 | 3 1/4 | 1.186 | 1.150 | 1.161 | 1.267 | 1.175 | 1.188 | 0.594 |
| 0.019 | 0.075 | # 12 | 4 1/4 | 1.058 | 1.046 | 1.073 | 1.057 | 1.045 | 1.056 | 0.528 |
| 0.019 | 0.075 | # 12 | 6 3/8 | 1.097 | 0.978 | 1.008 | 1.161 | 1.070 | 1.063 | 0.531 |
| 0.019 | 0.075 | # 14 | 0 | 1.744 | 1.624 | 1.746 | 1.647 | 1.413 | 1.635 | 0.817 |
| 0.019 | 0.075 | # 14 | 3 1/4 | 1.103 | 1.268 | 1.203 | 1.338 | 1.086 | 1.200 | 0.600 |
| 0.019 | 0.075 | # 14 | 4 1/4 | 1.100 | 1.157 | 1.169 | 1.070 | 1.163 | 1.132 | 0.566 |
| 0.019 | 0.075 | # 14 | 6 3/8 | 0.959 | 1.076 | 1.017 | 1.013 | 1.130 | 1.039 | 0.520 |

## Table A9. Test Results for 24x16 Series

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | 1 (kips) | 2 (kips) | Test 3 (kips) | 4 (kips) | 5 (kips) | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.023 | 0.058 | # 8 | 0 | 1.701 | 1.783 | 1.974 | 1.866 | 1.586 | 1.782 | 0.891 |
| 0.023 | 0.058 | # 8 | 3 1/4 | 1.376 | 1.353 | 1.243 | 1.409 | 1.400 | 1.356 | 0.678 |
| 0.023 | 0.058 | # 8 | 4 1/4 | 1.281 | 1.257 | 1.258 | 1.478 | 1.299 | 1.315 | 0.657 |
| 0.023 | 0.058 | # 8 | 6 3/8 | 1.318 | 1.216 | 1.228 | 1.181 | 1.192 | 1.227 | 0.614 |
| 0.023 | 0.058 | # 10 | 3 1/4 | 1.343 | 1.533 | 1.464 | 1.285 | 1.273 | 1.380 | 0.690 |
| 0.023 | 0.058 | # 10 | 4 1/4 | 1.285 | 1.549 | 1.326 | 1.298 | 1.257 | 1.343 | 0.672 |
| 0.023 | 0.058 | # 10 | 6 3/8 | 1.309 | 1.069 | 1.068 | 1.516 | 1.343 | 1.261 | 0.631 |
| 0.023 | 0.058 | # 12 | 3 1/4 | 1.698 | 1.250 | 1.802 | 1.664 | 1.550 | 1.679 | 0.839 |
| 0.023 | 0.058 | # 12 | 4 1/4 | 1.692 | 1.707 | 1.558 | 1.565 | 1.368 | 1.578 | 0.789 |
| 0.023 | 0.058 | # 12 | 6 3/8 | 1.568 | 1.417 | 1.558 | 1.425 | 1.436 | 1.481 | 0.740 |
| 0.023 | 0.058 | # 14 | 0 | 1.937 | 2.072 | 1.904 | 2.441 | 2.093 | 2.089 | 1.045 |
| 0.023 | 0.058 | # 14 | 3 1/4 | 1.780 | 1.547 | 1.676 | 1.498 | 1.707 | 1.642 | 0.821 |
| 0.023 | 0.058 | # 14 | 4 1/4 | 1.433 | 1.88 | 1.457 | 1.817 | 1.485 | 1.614 | 0.807 |
| 0.023 | 0.058 | # 14 | 6 3/8 | 1.458 | 1.442 | 1.539 | 1.413 | 1.496 | 1.470 | 0.735 |

## Table A10. Test Results for 22x18 Series

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | | | Test | | | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 (kips) | 2 (kips) | 3 (kips) | 4 (kips) | 5 (kips) | | |
| 0.030 | 0.044 | # 8 | 0 | 1.529 | 1.556 | 1.472 | 1.495 | 1.516 | 1.514 | 0.757 |
| 0.030 | 0.044 | # 8 | 3 1/4 | 1.326 | 1.351 | 1.297 | 1.296 | 1.343 | 1.323 | 0.661 |
| 0.030 | 0.044 | # 8 | 4 1/4 | 1.227 | 1.338 | 1.234 | 1.395 | 1.292 | 1.297 | 0.649 |
| 0.030 | 0.044 | # 8 | 6 3/8 | 1.356 | 1.266 | 1.119 | 1.292 | 1.246 | 1.256 | 0.628 |
| 0.030 | 0.044 | # 10 | 3 1/4 | 1.421 | 1.264 | 1.238 | 1.297 | 1.306 | 1.305 | 0.653 |
| 0.030 | 0.044 | # 10 | 4 1/4 | 1.356 | 1.313 | 1.460 | 1.379 | 1.282 | 1.358 | 0.679 |
| 0.030 | 0.044 | # 10 | 6 3/8 | 1.359 | 1.256 | 1.171 | 1.289 | 1.360 | 1.287 | 0.644 |
| 0.030 | 0.044 | # 12 | 3 1/4 | 1.413 | 1.430 | 1.441 | 1.446 | 1.487 | 1.443 | 0.722 |
| 0.030 | 0.044 | # 12 | 4 1/4 | 1.430 | 1.508 | 1.383 | 1.359 | 1.363 | 1.409 | 0.704 |
| 0.030 | 0.044 | # 12 | 6 3/8 | 1.413 | 1.569 | 1.346 | 1.486 | 1.525 | 1.468 | 0.734 |
| 0.030 | 0.044 | # 14 | 0 | 1.787 | 2.042 | 1.876 | 1.844 | 1.816 | 1.873 | 0.937 |
| 0.030 | 0.044 | # 14 | 3 1/4 | 1.665 | 1.693 | 1.738 | 1.673 | 1.680 | 1.690 | 0.845 |
| 0.030 | 0.044 | # 14 | 4 1/4 | 1.555 | 1.666 | 1.549 | 1.557 | 1.542 | 1.574 | 0.787 |
| 0.030 | 0.044 | # 14 | 6 3/8 | 1.707 | 1.490 | 1.766 | 1.703 | 1.487 | 1.631 | 0.815 |

## Table A11. Test Results for 22x12 Series

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | | | Test | | | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 (kips) | 2 (kips) | 3 (kips) | 4 (kips) | 5 (kips) | | |
| 0.031 | 0.106 | # 8 | 0 | | | | | | | |
| 0.031 | 0.106 | # 8 | 3 1/4 | | | | | | | |
| 0.031 | 0.106 | # 8 | 4 1/4 | | | | | | | |
| 0.031 | 0.106 | # 8 | 6 3/8 | | | | | | | |
| 0.031 | 0.106 | # 10 | 3 1/4 | 2.257 | 2.029 | 2.19 | 2.212 | 2.083 | 2.154 | 1.077 |
| 0.031 | 0.106 | # 10 | 4 1/4 | 1.872 | 1.979 | 2.027 | 2.095 | 1.878 | 1.970 | 0.985 |
| 0.031 | 0.106 | # 10 | 6 3/8 | 2.101 | 1.966 | 2.084 | 1.891 | 2.024 | 2.013 | 1.007 |
| 0.031 | 0.106 | # 12 | 3 1/4 | 2.46 | 2.427 | 2.369 | 2.421 | 2.536 | 2.443 | 1.221 |
| 0.031 | 0.106 | # 12 | 4 1/4 | 2.218 | 2.438 | 2.352 | 2.605 | 2.236 | 2.370 | 1.185 |
| 0.031 | 0.106 | # 12 | 6 3/8 | 2.095 | 2.146 | 2.335 | 2.187 | 2.074 | 2.167 | 1.084 |
| 0.031 | 0.106 | # 14 | 0 | 2.824 | 2.898 | 2.886 | 2.807 | 3.017 | 2.886 | 1.443 |
| 0.031 | 0.106 | # 14 | 3 1/4 | 2.241 | 2.342 | 2.312 | 2.248 | 2.787 | 2.386 | 1.193 |
| 0.031 | 0.106 | # 14 | 4 1/4 | 2.183 | 2.264 | 2.216 | 1.935 | 2.551 | 2.230 | 1.115 |
| 0.031 | 0.106 | # 14 | 6 3/8 | 2.062 | 2.109 | 2.079 | 2.145 | 2.084 | 2.096 | 1.048 |

## Table A12. Test Results for 18x18 Series

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | | | Test | | | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 (kips) | 2 (kips) | 3 (kips) | 4 (kips) | 5 (kips) | | |
| 0.045 | 0.045 | # 8 | 0 | 1.999 | 1.986 | 1.899 | 2.100 | 2.006 | 1.998 | 0.999 |
| 0.045 | 0.045 | # 8 | 3 1/4 | 1.811 | 1.749 | 1.769 | 1.683 | 1.497 | 1.702 | 0.851 |
| 0.045 | 0.045 | # 8 | 4 1/4 | 1.643 | 1.640 | 1.565 | 1.495 | 1.641 | 1.597 | 0.798 |
| 0.045 | 0.045 | # 8 | 6 3/8 | | | | | | | |
| 0.045 | 0.045 | # 10 | 3 1/4 | 1.604 | 1.695 | 1.594 | 1.686 | 1.624 | 1.641 | 0.820 |
| 0.045 | 0.045 | # 10 | 4 1/4 | 1.212 | 1.531 | 1.421 | 1.414 | 1.285 | 1.373 | 0.686 |
| 0.045 | 0.045 | # 10 | 6 3/8 | 1.175 | 1.319 | 1.322 | 1.473 | 1.281 | 1.314 | 0.657 |
| 0.045 | 0.045 | # 12 | 3 1/4 | 1.855 | 1.887 | 1.844 | 1.777 | 1.746 | 1.822 | 0.911 |
| 0.045 | 0.045 | # 12 | 4 1/4 | 1.674 | 1.562 | 1.709 | 1.852 | 1.641 | 1.688 | 0.844 |
| 0.045 | 0.045 | # 12 | 6 3/8 | 1.480 | 1.435 | 1.402 | 1.420 | 1.323 | 1.412 | 0.706 |
| 0.045 | 0.045 | # 14 | 0 | 2.319 | 2.352 | 2.205 | 2.211 | 2.282 | 2.274 | 1.137 |
| 0.045 | 0.045 | # 14 | 3 1/4 | 1.783 | 1.836 | 1.708 | 1.689 | 1.822 | 1.768 | 0.884 |
| 0.045 | 0.045 | # 14 | 4 1/4 | 1.727 | 1.892 | 1.886 | 1.785 | 1.839 | 1.826 | 0.913 |
| 0.045 | 0.045 | # 14 | 6 3/8 | 1.553 | 1.499 | 1.665 | 1.472 | 1.719 | 1.582 | 0.791 |

## Table A13. Test Results for 18x12 Series

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | | | Test | | | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 (kips) | 2 (kips) | 3 (kips) | 4 (kips) | 5 (kips) | | |
| 0.045 | 0.117 | # 8 | 0 | | | | | | | |
| 0.045 | 0.117 | # 8 | 3 1/4 | | | | | | | |
| 0.045 | 0.117 | # 8 | 4 1/4 | | | | | | | |
| 0.045 | 0.117 | # 8 | 6 3/8 | | | | | | | |
| 0.045 | 0.117 | # 10 | 3 1/4 | 3.395 | 3.141 | 3.060 | 3.173 | 3.184 | 3.191 | 1.595 |
| 0.045 | 0.117 | # 10 | 4 1/4 | 3.159 | 3.028 | 3.139 | 3.102 | 2.938 | 3.073 | 1.537 |
| 0.045 | 0.117 | # 10 | 6 3/8 | 3.023 | 3.159 | 3.060 | 3.195 | 2.938 | 3.075 | 1.538 |
| 0.045 | 0.117 | # 12 | 3 1/4 | 3.671 | 3.598 | 3.247 | 3.352 | 3.257 | 3.425 | 1.713 |
| 0.045 | 0.117 | # 12 | 4 1/4 | 3.312 | 3.370 | 3.215 | 3.197 | 3.154 | 3.250 | 1.625 |
| 0.045 | 0.117 | # 12 | 6 3/8 | 3.302 | 3.526 | 3.304 | 3.455 | 3.250 | 3.367 | 1.684 |
| 0.045 | 0.117 | # 14 | 0 | 4.247 | 4.246 | 4.228 | 4.246 | 4.273 | 4.248 | 2.124 |
| 0.045 | 0.117 | # 14 | 3 1/4 | 3.767 | 3.531 | 3.461 | 3.614 | 3.954 | 3.665 | 1.833 |
| 0.045 | 0.117 | # 14 | 4 1/4 | 3.399 | 3.357 | 3.326 | 3.561 | 3.453 | 3.419 | 1.710 |
| 0.045 | 0.117 | # 14 | 6 3/8 | 3.363 | 3.434 | 3.453 | 3.236 | 3.067 | 3.311 | 1.655 |

**Table A14. Test Results for 16x16 Series**

| $t_1$ | $t_2$ | Screw | Insulation Thickness (in) | 1 (kips) | 2 (kips) | Test 3 (kips) | 4 (kips) | 5 (kips) | Average (kips) | Strength per screw (kips) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.057 | 0.057 | # 8 | 0 | 2.118 | 2.138 | 2.111 | 2.188 | 2.115 | 2.134 | 1.067 |
| 0.057 | 0.057 | # 8 | 3 1/4 | 1.529 | 1.753 | 1.698 | 1.868 | 1.768 | 1.723 | 0.862 |
| 0.057 | 0.057 | # 8 | 4 1/4 | 1.690 | 1.476 | 1.912 | 1.647 | 1.463 | 1.638 | 0.819 |
| 0.057 | 0.057 | # 8 | 6 3/8 | | | | | | | |
| 0.057 | 0.057 | # 10 | 3 1/4 | 1.926 | 1.653 | 1.740 | 1.629 | 1.701 | 1.730 | 0.865 |
| 0.057 | 0.057 | # 10 | 4 1/4 | 1.798 | 1.687 | 1.711 | 1.685 | 1.574 | 1.691 | 0.846 |
| 0.057 | 0.057 | # 10 | 6 3/8 | | | | | | | |
| 0.057 | 0.057 | # 12 | 3 1/4 | 1.917 | 1.926 | 2.019 | 1.945 | 1.912 | 1.944 | 0.972 |
| 0.057 | 0.057 | # 12 | 4 1/4 | 1.723 | 1.812 | 1.885 | 1.898 | 1.869 | 1.837 | 0.919 |
| 0.057 | 0.057 | # 12 | 6 3/8 | 1.662 | 1.765 | 1.736 | 1.517 | 1.779 | 1.692 | 0.846 |
| 0.057 | 0.057 | # 14 | 0 | 2.372 | 2.410 | 2.489 | 2.568 | 2.438 | 2.455 | 1.228 |
| 0.057 | 0.057 | # 14 | 3 1/4 | 2.235 | 2.251 | 2.199 | 2.215 | 2.210 | 2.222 | 1.111 |
| 0.057 | 0.057 | # 14 | 4 1/4 | 2.288 | 2.313 | 2.325 | 2.096 | 2.178 | 2.240 | 1.120 |
| 0.057 | 0.057 | # 14 | 6 3/8 | 1.973 | 1.913 | 2.005 | 1.906 | 1.879 | 1.935 | 0.968 |

# APPENDIX B

# DIAPHRAGM TEST DATA

Table B1. Coupon Test Results

| Gage | Material Type | Test # | Thickness (in.) | Width (in.) | Yield Load (kips) | Peak Load (kips) | Avg Fy (ksi) | Avg Fu (ksi) |
|---|---|---|---|---|---|---|---|---|
| **12** | **Purlin** | 1 | 0.104 | 1.5 | 10.55 | 12.10 | **67.3** | **77.2** |
| | | 2 | 0.104 | 1.5 | 10.45 | 11.98 | | |
| **12** | **Eve Strut** | 1 | 0.104 | 1.5 | 9.67 | 11.07 | **62.3** | **70.7** |
| | | 2 | 0.104 | 1.5 | 9.77 | 11.00 | | |
| **14** | **Eve Strut** | 1 | 0.068 | 1.5 | 7.02 | 7.83 | **68.7** | **76.9** |
| | | 2 | 0.068 | 1.5 | 6.99 | 7.86 | | |
| **16** | **Purlin** | 1 | 0.060 | 1.5 | 5.63 | 6.43 | **62.0** | **70.9** |
| | | 2 | 0.060 | 1.5 | 5.53 | 6.33 | | |
| **26** | **5'-2" Deck** | 1 | 0.018 | 0.5 | 0.96 | 0.990 | **107.2** | **110.7** |
| | | 2 | 0.018 | 0.5 | 0.97 | 1.003 | | |
| **26** | **10'-4" Deck** | 1 | 0.018 | 0.5 | 1.00 | 1.045 | **111.1** | **116.0** |
| | | 2 | 0.018 | 0.5 | 0.98 | 1.016 | | |
| | | 3 | 0.018 | 0.5 | 1.02 | 1.072 | | |

**Table B2. 26x12-0 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | $\Delta_f$ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.001 | 0.000 | 0.011 | 0.000 | 0 | 0.000 |
| 2 | 0.001 | 0.000 | 0.156 | -0.010 | 871 | 0.166 |
| 3 | 0.001 | 0.000 | 0.030 | -0.007 | 13 | 0.036 |
| 4 | 0.000 | 0.001 | 0.113 | -0.007 | 508 | 0.119 |
| 5 | 0.000 | 0.000 | 0.177 | -0.010 | 988 | 0.188 |
| 6 | 0.000 | 0.000 | 0.256 | -0.016 | 1405 | 0.273 |
| 7 | 0.000 | 0.000 | 0.394 | -0.029 | 2018 | 0.425 |
| 8 | 0.001 | 0.000 | 0.480 | -0.034 | 2333 | 0.515 |
| 9 | 0.001 | 0.000 | 0.651 | -0.039 | 2887 | 0.692 |
| 10 | 0.000 | 0.000 | 0.776 | -0.043 | 3194 | 0.822 |
| 11 | 0.001 | 0.001 | 0.922 | -0.049 | 3540 | 0.972 |
| 12 | 0.002 | 0.001 | 1.140 | -0.055 | 3944 | 1.196 |
| 13 | 0.001 | 0.001 | 1.385 | -0.060 | 4375 | 1.447 |
| 14 | 0.002 | 0.002 | 1.640 | -0.062 | 4715 | 1.702 |
| 15 | 0.001 | 0.001 | 1.900 | -0.061 | 5138 | 1.963 |
| 16 | 0.001 | 0.002 | 2.242 | -0.061 | 5458 | 2.304 |
| 17 | 0.001 | 0.002 | 2.652 | -0.057 | 5801 | 2.710 |
| 18 | 0.001 | 0.004 | 2.992 | -0.050 | 6106 | 3.040 |
| 19 | -0.004 | 0.004 | 3.505 | -0.027 | 5900 | 3.534 |
| 20 | -0.017 | 0.005 | 3.984 | -0.001 | 6098 | 3.998 |
| 21 | -0.023 | 0.004 | 4.182 | 0.013 | 6111 | 4.189 |
| 22 | -0.031 | 0.005 | 4.432 | 0.024 | 6311 | 4.434 |
| 23 | -0.050 | 0.005 | 4.926 | 0.054 | 6380 | 4.917 |
| 24 | -0.074 | 0.006 | 5.407 | 0.088 | 6551 | 5.386 |
| 25 | -0.106 | 0.007 | 5.989 | 0.127 | 6679 | 5.960 |
| 26 | -0.138 | 0.008 | 6.488 | 0.173 | 6721 | 6.443 |
| 27 | -0.174 | 0.008 | 7.017 | 0.230 | 6376 | 6.949 |
| 28 | -0.219 | 0.008 | 7.553 | 0.291 | 6200 | 7.468 |
| 29 | -0.267 | 0.008 | 8.091 | 0.354 | 6358 | 7.990 |
| 30 | -0.324 | 0.008 | 8.685 | 0.437 | 5810 | 8.556 |
| 31 | -0.373 | 0.008 | 9.132 | 0.508 | 5063 | 8.980 |

**Table B3. 26x12-3 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | $\Delta_f$ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.001 | -0.001 | -0.001 | 0.000 | 0 | 0.000 |
| 2 | 0.000 | -0.001 | 0.180 | -0.009 | 760 | 0.191 |
| 3 | 0.001 | 0.000 | 0.025 | -0.002 | 8 | 0.026 |
| 4 | 0.001 | 0.000 | 0.138 | -0.006 | 521 | 0.143 |
| 5 | 0.001 | 0.000 | 0.226 | -0.011 | 1111 | 0.237 |
| 6 | 0.001 | 0.000 | 0.343 | -0.021 | 1544 | 0.364 |
| 7 | 0.002 | 0.000 | 0.477 | -0.028 | 2061 | 0.505 |
| 8 | 0.002 | 0.000 | 0.625 | -0.032 | 2544 | 0.657 |
| 9 | 0.004 | 0.000 | 0.799 | -0.039 | 3021 | 0.836 |
| 10 | 0.005 | 0.000 | 1.019 | -0.045 | 3515 | 1.062 |
| 11 | 0.006 | 0.000 | 1.329 | -0.049 | 4004 | 1.375 |
| 12 | 0.006 | 0.000 | 1.670 | -0.051 | 4502 | 1.718 |
| 13 | 0.006 | 0.000 | 2.120 | -0.051 | 5003 | 2.168 |
| 14 | 0.001 | 0.001 | 2.743 | -0.039 | 5490 | 2.783 |
| 15 | -0.034 | 0.001 | 4.118 | 0.021 | 6103 | 4.131 |
| 16 | -0.052 | 0.002 | 4.579 | 0.043 | 6348 | 4.587 |
| 17 | -0.064 | 0.002 | 4.832 | 0.060 | 6518 | 4.834 |
| 18 | -0.086 | 0.002 | 5.339 | 0.099 | 6331 | 5.323 |
| 19 | -0.097 | 0.004 | 5.576 | 0.117 | 6584 | 5.551 |
| 20 | -0.114 | 0.004 | 5.817 | 0.134 | 6578 | 5.792 |
| 21 | -0.158 | 0.004 | 6.451 | 0.195 | 6724 | 6.408 |
| 22 | -0.165 | 0.006 | 6.592 | 0.211 | 6325 | 6.537 |
| 23 | -0.230 | 0.006 | 7.434 | 0.284 | 6629 | 7.370 |
| 24 | -0.299 | 0.007 | 8.163 | 0.371 | 6688 | 8.079 |
| 25 | -0.331 | 0.008 | 8.503 | 0.419 | 6070 | 8.401 |
| 26 | -0.395 | 0.008 | 9.139 | 0.520 | 5052 | 8.998 |

**Table B4. 26x12-4 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | $\Delta_f$ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.000 | 0.001 | 0.000 | 0.000 | 0 | 0.000 |
| 2 | -0.001 | 0.001 | 0.175 | -0.009 | 638 | 0.185 |
| 3 | -0.001 | 0.001 | 0.032 | -0.005 | -2 | 0.037 |
| 4 | 0.000 | 0.001 | 0.100 | -0.006 | 443 | 0.105 |
| 5 | 0.000 | 0.001 | 0.251 | -0.012 | 1120 | 0.263 |
| 6 | 0.000 | 0.001 | 0.339 | -0.018 | 1524 | 0.357 |
| 7 | 0.000 | 0.001 | 0.446 | -0.021 | 1838 | 0.467 |
| 8 | -0.001 | 0.001 | 0.552 | -0.026 | 2179 | 0.580 |
| 9 | -0.001 | 0.001 | 0.627 | -0.027 | 2389 | 0.656 |
| 10 | 0.000 | 0.001 | 0.745 | -0.030 | 2684 | 0.776 |
| 11 | 0.000 | 0.001 | 0.873 | -0.034 | 2962 | 0.908 |
| 12 | 0.000 | 0.001 | 1.026 | -0.037 | 3274 | 1.064 |
| 13 | 0.000 | 0.001 | 1.190 | -0.038 | 3579 | 1.230 |
| 14 | 0.000 | 0.001 | 1.379 | -0.039 | 3874 | 1.420 |
| 15 | 0.000 | 0.001 | 1.671 | -0.039 | 4184 | 1.712 |
| 16 | 0.000 | 0.001 | 2.000 | -0.039 | 4508 | 2.041 |
| 17 | -0.001 | 0.001 | 2.163 | -0.038 | 4758 | 2.204 |
| 18 | -0.002 | 0.002 | 2.330 | -0.038 | 5032 | 2.371 |
| 19 | -0.002 | 0.002 | 2.424 | -0.030 | 4723 | 2.456 |
| 20 | -0.002 | 0.002 | 2.550 | -0.029 | 5072 | 2.581 |
| 21 | -0.004 | 0.002 | 2.623 | -0.029 | 5155 | 2.656 |
| 22 | -0.005 | 0.002 | 2.729 | -0.027 | 5213 | 2.761 |
| 23 | -0.007 | 0.002 | 2.841 | -0.023 | 5335 | 2.871 |
| 24 | -0.010 | 0.002 | 2.949 | -0.021 | 5400 | 2.980 |
| 25 | -0.012 | 0.002 | 3.048 | -0.018 | 5511 | 3.078 |
| 26 | -0.012 | 0.002 | 3.107 | -0.017 | 5550 | 3.136 |
| 27 | -0.015 | 0.002 | 3.168 | -0.016 | 5621 | 3.199 |
| 28 | -0.016 | 0.002 | 3.237 | -0.011 | 5668 | 3.264 |
| 29 | -0.017 | 0.002 | 3.280 | -0.010 | 5670 | 3.307 |
| 30 | -0.020 | 0.004 | 3.360 | 0.000 | 5385 | 3.377 |
| 31 | -0.025 | 0.002 | 3.505 | 0.005 | 5543 | 3.524 |
| 32 | -0.026 | 0.002 | 3.555 | 0.010 | 5323 | 3.570 |
| 33 | -0.028 | 0.002 | 3.685 | 0.017 | 5368 | 3.695 |
| 34 | -0.030 | 0.002 | 3.751 | 0.021 | 5398 | 3.759 |
| 35 | -0.036 | 0.002 | 3.893 | 0.029 | 5501 | 3.898 |
| 36 | -0.042 | 0.006 | 4.016 | 0.034 | 5590 | 4.019 |
| 37 | -0.047 | 0.006 | 4.169 | 0.039 | 5700 | 4.172 |
| 38 | -0.055 | 0.006 | 4.325 | 0.046 | 5851 | 4.329 |
| 39 | -0.059 | 0.006 | 4.393 | 0.051 | 5856 | 4.396 |
| 40 | -0.062 | 0.006 | 4.480 | 0.057 | 5948 | 4.479 |
| 41 | -0.066 | 0.006 | 4.562 | 0.062 | 6023 | 4.560 |
| 42 | -0.075 | 0.006 | 4.727 | 0.072 | 6115 | 4.724 |
| 43 | -0.081 | 0.006 | 4.848 | 0.074 | 6201 | 4.849 |
| 44 | -0.089 | 0.006 | 4.957 | 0.084 | 6255 | 4.956 |

## Table B4. 26x12-4 Test Data

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | $\Delta_f$ (in) |
|---|---|---|---|---|---|---|
| 45 | -0.096 | 0.006 | 5.077 | 0.094 | 6208 | 5.073133 |
| 46 | -0.107 | 0.008 | 5.268 | 0.106 | 6328 | 5.261067 |
| 47 | -0.113 | 0.01 | 5.349 | 0.118 | 6173 | 5.333667 |
| 48 | -0.121 | 0.011 | 5.488 | 0.122 | 6313 | 5.475933 |
| 49 | -0.132 | 0.01 | 5.669 | 0.136 | 6398 | 5.654733 |
| 50 | -0.145 | 0.011 | 5.879 | 0.153 | 6075 | 5.859467 |
| 51 | -0.155 | 0.011 | 6.042 | 0.172 | 5836 | 6.012867 |
| 52 | -0.164 | 0.011 | 6.208 | 0.188 | 5840 | 6.1714 |
| 53 | -0.177 | 0.01 | 6.375 | 0.202 | 5881 | 6.338333 |
| 54 | -0.194 | 0.01 | 6.595 | 0.223 | 5913 | 6.554067 |
| 55 | -0.217 | 0.013 | 6.841 | 0.248 | 6145 | 6.794933 |
| 56 | -0.24 | 0.014 | 7.13 | 0.276 | 6381 | 7.0776 |
| 57 | -0.273 | 0.012 | 7.49 | 0.313 | 6400 | 7.435333 |
| 58 | -0.304 | 0.012 | 7.804 | 0.352 | 6308 | 7.7408 |
| 59 | -0.367 | 0.013 | 8.458 | 0.443 | 5758 | 8.363933 |

**Table B5. 26x12-6 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | $\Delta_f$ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.000 | 0.000 | 0.002 | -0.001 | 0 | 0.000 |
| 2 | 0.000 | 0.000 | 0.229 | -0.012 | 1035 | 0.242 |
| 3 | 0.000 | 0.001 | 0.041 | -0.009 | 8 | 0.050 |
| 4 | 0.002 | 0.000 | 0.173 | -0.012 | 633 | 0.184 |
| 5 | 0.001 | 0.000 | 0.278 | -0.013 | 1253 | 0.291 |
| 6 | 0.002 | 0.000 | 0.441 | -0.027 | 1828 | 0.468 |
| 7 | 0.002 | 0.000 | 0.627 | -0.034 | 2374 | 0.661 |
| 8 | 0.002 | 0.000 | 0.900 | -0.040 | 3001 | 0.941 |
| 9 | 0.002 | 0.000 | 1.210 | -0.043 | 3497 | 1.254 |
| 10 | 0.002 | 0.000 | 1.501 | -0.044 | 3950 | 1.546 |
| 11 | 0.002 | 0.000 | 1.931 | -0.043 | 4444 | 1.975 |
| 12 | 0.001 | 0.001 | 2.387 | -0.039 | 4673 | 2.427 |
| 13 | -0.001 | 0.001 | 2.806 | -0.034 | 5265 | 2.842 |
| 14 | -0.011 | 0.001 | 3.291 | -0.016 | 5601 | 3.319 |
| 15 | -0.032 | 0.001 | 4.067 | 0.024 | 5598 | 4.075 |
| 16 | -0.053 | 0.001 | 4.559 | 0.051 | 5973 | 4.560 |
| 17 | -0.087 | 0.002 | 5.353 | 0.122 | 5262 | 5.314 |
| 18 | -0.124 | 0.002 | 6.007 | 0.173 | 5516 | 5.953 |
| 19 | -0.196 | 0.002 | 6.992 | 0.263 | 5921 | 6.919 |
| 20 | -0.286 | 0.001 | 7.996 | 0.379 | 6031 | 7.896 |
| 21 | -0.341 | 0.002 | 8.601 | 0.460 | 5685 | 8.472 |
| 22 | -0.425 | 0.002 | 9.325 | 0.560 | 5555 | 9.179 |

### Table B6.  26x16-0 Test Data

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | Δ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.000 | 0.001 | 0.000 | 0.000 | 0 | 0.000 |
| 2 | -0.001 | 0.000 | 0.152 | -0.002 | 483 | 0.155 |
| 3 | 0.000 | 0.001 | 0.023 | -0.002 | 5 | 0.024 |
| 4 | -0.001 | 0.000 | 0.168 | -0.002 | 533 | 0.171 |
| 5 | 0.001 | 0.000 | 0.387 | -0.012 | 993 | 0.399 |
| 6 | 0.002 | 0.001 | 0.742 | -0.017 | 1473 | 0.757 |
| 7 | 0.004 | 0.000 | 1.280 | -0.016 | 2066 | 1.293 |
| 8 | 0.004 | 0.001 | 1.714 | -0.017 | 2498 | 1.727 |
| 9 | 0.004 | 0.000 | 2.106 | -0.009 | 2779 | 2.111 |
| 10 | 0.001 | 0.001 | 2.607 | 0.002 | 3169 | 2.603 |
| 11 | -0.014 | 0.000 | 3.367 | 0.038 | 3451 | 3.341 |
| 12 | -0.022 | 0.000 | 3.592 | 0.048 | 3564 | 3.564 |
| 13 | -0.043 | 0.000 | 4.197 | 0.091 | 3635 | 4.146 |
| 14 | -0.055 | 0.001 | 4.482 | 0.106 | 3742 | 4.427 |
| 15 | -0.080 | 0.000 | 5.000 | 0.139 | 3987 | 4.937 |
| 16 | -0.105 | 0.000 | 5.465 | 0.181 | 4255 | 5.384 |
| 17 | -0.192 | 0.001 | 6.761 | 0.302 | 4409 | 6.643 |
| 18 | -0.260 | 0.001 | 7.510 | 0.380 | 4580 | 7.381 |
| 19 | -0.334 | 0.001 | 8.253 | 0.474 | 4758 | 8.103 |
| 20 | -0.377 | 0.001 | 8.685 | 0.538 | 4362 | 8.512 |
| 21 | -0.441 | 0.001 | 9.046 | 0.597 | 4230 | 8.879 |

**Table B7. 26x16-3 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | Δ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.006 | 0.019 | 0.005 | -0.006 | 0 | 0.000 |
| 2 | 0.001 | 0.001 | 0.149 | -0.002 | 530 | 0.149 |
| 3 | 0.006 | 0.019 | 0.020 | -0.011 | 13 | 0.006 |
| 4 | 0.002 | 0.005 | 0.164 | -0.007 | 531 | 0.164 |
| 5 | 0.002 | 0.006 | 0.363 | -0.011 | 986 | 0.367 |
| 6 | 0.006 | 0.006 | 0.684 | -0.015 | 1516 | 0.688 |
| 7 | 0.007 | 0.006 | 1.043 | -0.017 | 1998 | 1.048 |
| 8 | 0.014 | 0.019 | 1.578 | -0.022 | 2507 | 1.568 |
| 9 | 0.007 | 0.007 | 2.372 | -0.004 | 3004 | 2.362 |
| 10 | -0.009 | 0.020 | 3.358 | 0.037 | 3502 | 3.308 |
| 11 | -0.085 | 0.020 | 5.165 | 0.156 | 3789 | 5.069 |
| 12 | -0.158 | 0.007 | 6.236 | 0.258 | 3984 | 6.122 |
| 13 | -0.185 | 0.012 | 6.611 | 0.291 | 4105 | 6.486 |
| 14 | -0.219 | 0.020 | 7.044 | 0.336 | 4202 | 6.899 |
| 15 | -0.246 | 0.020 | 7.352 | 0.369 | 4295 | 7.201 |
| 16 | -0.366 | 0.020 | 8.580 | 0.538 | 3794 | 8.377 |
| 17 | -0.513 | 0.020 | 9.613 | 0.714 | 3885 | 9.379 |

**Table B8. 26x16-4 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | Δ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.004 | 0.000 | 0.000 | 0.000 | 0 | 0.000 |
| 2 | 0.002 | 0.001 | 0.208 | -0.004 | 560 | 0.209 |
| 3 | 0.004 | 0.001 | 0.022 | -0.004 | 3 | 0.021 |
| 4 | 0.001 | 0.001 | 0.205 | -0.004 | 571 | 0.207 |
| 5 | -0.004 | 0.001 | 0.413 | -0.009 | 1056 | 0.426 |
| 6 | 0.005 | 0.001 | 0.730 | -0.013 | 1521 | 0.738 |
| 7 | 0.007 | 0.002 | 1.190 | -0.016 | 2133 | 1.198 |
| 8 | 0.005 | 0.002 | 1.490 | -0.016 | 2502 | 1.500 |
| 9 | 0.000 | 0.002 | 1.990 | -0.011 | 3062 | 2.000 |
| 10 | -0.023 | 0.002 | 3.486 | 0.055 | 3499 | 3.450 |
| 11 | -0.069 | 0.004 | 4.637 | 0.132 | 3829 | 4.566 |
| 12 | -0.112 | 0.005 | 5.317 | 0.180 | 4234 | 5.239 |
| 13 | -0.159 | 0.004 | 6.139 | 0.264 | 3934 | 6.023 |
| 14 | -0.245 | 0.004 | 7.033 | 0.353 | 4295 | 6.914 |
| 15 | -0.305 | 0.005 | 7.736 | 0.438 | 4369 | 7.589 |
| 16 | -0.416 | 0.005 | 8.752 | 0.588 | 3767 | 8.564 |

**Table B9. 26x16-6 Test Data**

| ID | Δ 1 (in) | Δ 2 (in) | Δ 3 (in) | Δ 4 (in) | Load (lb) | Δ (in) |
|---|---|---|---|---|---|---|
| 1 | 0.000 | 0.000 | 0.000 | 0.001 | 0 | 0.000 |
| 2 | 0.001 | 0.000 | 0.202 | -0.007 | 555 | 0.208 |
| 3 | 0.001 | 0.000 | 0.018 | -0.004 | 7 | 0.021 |
| 4 | 0.001 | 0.000 | 0.215 | -0.007 | 573 | 0.221 |
| 5 | 0.005 | 0.000 | 0.470 | -0.016 | 1071 | 0.482 |
| 6 | 0.015 | 0.000 | 0.830 | -0.026 | 1509 | 0.842 |
| 7 | 0.018 | 0.000 | 1.329 | -0.028 | 2069 | 1.340 |
| 8 | 0.022 | 0.000 | 1.723 | -0.029 | 2469 | 1.730 |
| 9 | 0.022 | 0.000 | 2.281 | -0.029 | 3042 | 2.288 |
| 10 | 0.022 | 0.000 | 3.007 | -0.021 | 3500 | 3.006 |
| 11 | -0.014 | 0.000 | 4.573 | 0.049 | 4029 | 4.536 |
| 12 | -0.033 | 0.000 | 5.093 | 0.084 | 4175 | 5.039 |
| 13 | -0.059 | 0.001 | 5.617 | 0.113 | 4347 | 5.558 |
| 14 | -0.076 | 0.001 | 5.958 | 0.140 | 4484 | 5.889 |
| 15 | -0.107 | 0.001 | 6.461 | 0.178 | 4723 | 6.384 |
| 16 | -0.132 | 0.001 | 6.875 | 0.222 | 4402 | 6.778 |
| 17 | -0.272 | 0.001 | 8.590 | 0.413 | 3935 | 8.439 |

# APPENDIX C

# ANALYSIS OF TEST DATA

## Table C1. Comparison of Test Results for 26x14 Series to North American Specification

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.019 | 0.0745 | 0.164 | 0.00 | 3.92 | 0.37 | 1.44 | 1.50 | 0.37 | 0.81 | **2.22** |
| 0.019 | 0.0745 | 0.164 | 0.09 | 3.92 | 0.37 | 1.44 | 1.50 | 0.37 | 0.58 | **1.59** |
| 0.019 | 0.0745 | 0.164 | 0.12 | 3.92 | 0.37 | 1.44 | 1.50 | 0.37 | 0.58 | **1.58** |
| 0.019 | 0.0745 | 0.164 | 0.15 | 3.92 | 0.37 | 1.44 | 1.50 | 0.37 | 0.56 | **1.52** |
| 0.019 | 0.0745 | 0.190 | 0.09 | 3.92 | 0.42 | 1.66 | 1.62 | 0.42 | 0.67 | **1.57** |
| 0.019 | 0.0745 | 0.190 | 0.12 | 3.92 | 0.42 | 1.66 | 1.62 | 0.42 | 0.59 | **1.38** |
| 0.019 | 0.0745 | 0.190 | 0.15 | 3.92 | 0.42 | 1.66 | 1.62 | 0.42 | 0.55 | **1.30** |
| 0.019 | 0.0745 | 0.216 | 0.09 | 3.92 | 0.48 | 1.89 | 1.73 | 0.48 | 0.59 | **1.23** |
| 0.019 | 0.0745 | 0.216 | 0.12 | 3.92 | 0.48 | 1.89 | 1.73 | 0.48 | 0.53 | **1.10** |
| 0.019 | 0.0745 | 0.216 | 0.15 | 3.92 | 0.48 | 1.89 | 1.73 | 0.48 | 0.53 | **1.10** |
| 0.019 | 0.0745 | 0.240 | 0.00 | 3.92 | 0.54 | 2.10 | 1.82 | 0.54 | 0.82 | **1.53** |
| 0.019 | 0.0745 | 0.240 | 0.09 | 3.92 | 0.54 | 2.10 | 1.82 | 0.54 | 0.60 | **1.12** |
| 0.019 | 0.0745 | 0.240 | 0.12 | 3.92 | 0.54 | 2.10 | 1.82 | 0.54 | 0.57 | **1.06** |
| 0.019 | 0.0745 | 0.240 | 0.15 | 3.92 | 0.54 | 2.10 | 1.82 | 0.54 | 0.52 | **0.97** |

## Table C2. Comparison of Test Results for 24x16 Series to North American Specification

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.023 | 0.058 | 0.164 | 0.00 | 2.52 | 0.70 | 2.00 | 1.85 | 0.70 | 0.89 | **1.27** |
| 0.023 | 0.058 | 0.164 | 0.09 | 2.52 | 0.70 | 2.00 | 1.85 | 0.70 | 0.68 | **0.97** |
| 0.023 | 0.058 | 0.164 | 0.12 | 2.52 | 0.70 | 2.00 | 1.85 | 0.70 | 0.66 | **0.94** |
| 0.023 | 0.058 | 0.164 | 0.15 | 2.52 | 0.70 | 2.00 | 1.85 | 0.70 | 0.61 | **0.88** |
| 0.023 | 0.058 | 0.190 | 0.09 | 2.52 | 0.81 | 2.31 | 1.99 | 0.81 | 0.69 | **0.85** |
| 0.023 | 0.058 | 0.190 | 0.12 | 2.52 | 0.81 | 2.31 | 1.99 | 0.81 | 0.84 | **1.04** |
| 0.023 | 0.058 | 0.190 | 0.15 | 2.52 | 0.81 | 2.31 | 1.99 | 0.81 | 0.79 | **0.97** |
| 0.023 | 0.058 | 0.216 | 0.09 | 2.52 | 0.92 | 2.63 | 2.12 | 0.92 | 0.84 | **0.91** |
| 0.023 | 0.058 | 0.216 | 0.12 | 2.52 | 0.92 | 2.63 | 2.12 | 0.92 | 0.77 | **0.84** |
| 0.023 | 0.058 | 0.216 | 0.15 | 2.52 | 0.92 | 2.63 | 2.12 | 0.92 | 0.75 | **0.81** |
| 0.023 | 0.058 | 0.240 | 0.00 | 2.52 | 1.02 | 2.92 | 2.23 | 1.02 | 1.05 | **1.02** |
| 0.023 | 0.058 | 0.240 | 0.09 | 2.52 | 1.02 | 2.92 | 2.23 | 1.02 | 0.83 | **0.81** |
| 0.023 | 0.058 | 0.240 | 0.12 | 2.52 | 1.02 | 2.92 | 2.23 | 1.02 | 0.77 | **0.76** |
| 0.023 | 0.058 | 0.240 | 0.15 | 2.52 | 1.02 | 2.92 | 2.23 | 1.02 | 0.73 | **0.72** |

**Table C3. Comparison of Test Results for 22x18 Series to North American Specification**

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0295 | 0.0435 | 0.164 | 0.00 | 1.47 | 0.64 | 0.95 | 0.76 | 0.64 | 0.76 | **1.18** |
| 0.0295 | 0.0435 | 0.164 | 0.09 | 1.47 | 0.64 | 0.95 | 0.76 | 0.64 | 0.66 | **1.03** |
| 0.0295 | 0.0435 | 0.164 | 0.12 | 1.47 | 0.64 | 0.95 | 0.76 | 0.64 | 0.65 | **1.01** |
| 0.0295 | 0.0435 | 0.164 | 0.15 | 1.47 | 0.64 | 0.95 | 0.76 | 0.64 | 0.63 | **0.98** |
| 0.0295 | 0.0435 | 0.190 | 0.09 | 1.47 | 0.74 | 1.10 | 0.82 | 0.74 | 0.65 | **0.88** |
| 0.0295 | 0.0435 | 0.190 | 0.12 | 1.47 | 0.74 | 1.10 | 0.82 | 0.74 | 0.68 | **0.91** |
| 0.0295 | 0.0435 | 0.190 | 0.15 | 1.47 | 0.74 | 1.10 | 0.82 | 0.74 | 0.64 | **0.86** |
| 0.0295 | 0.0435 | 0.216 | 0.09 | 1.47 | 0.85 | 1.25 | 0.87 | 0.85 | 0.72 | **0.85** |
| 0.0295 | 0.0435 | 0.216 | 0.12 | 1.47 | 0.85 | 1.25 | 0.87 | 0.85 | 0.70 | **0.83** |
| 0.0295 | 0.0435 | 0.216 | 0.15 | 1.47 | 0.85 | 1.25 | 0.87 | 0.85 | 0.73 | **0.87** |
| 0.0295 | 0.0435 | 0.240 | 0.00 | 1.47 | 0.94 | 1.39 | 0.92 | 0.93 | 0.94 | **1.01** |
| 0.0295 | 0.0435 | 0.240 | 0.09 | 1.47 | 0.94 | 1.39 | 0.92 | 0.93 | 0.84 | **0.91** |
| 0.0295 | 0.0435 | 0.240 | 0.12 | 1.47 | 0.94 | 1.39 | 0.92 | 0.93 | 0.79 | **0.85** |
| 0.0295 | 0.0435 | 0.240 | 0.15 | 1.47 | 0.94 | 1.39 | 0.92 | 0.93 | 0.82 | **0.88** |

**Table C4. Comparison of Test Results for 22x12 Series to North American Specification**

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.031 | 0.106 | 0.164 | 0.00 | 3.42 | 0.86 | 3.43 | 4.29 | 0.86 | | |
| 0.031 | 0.106 | 0.164 | 0.09 | 3.42 | 0.86 | 3.43 | 4.29 | 0.86 | | |
| 0.031 | 0.106 | 0.164 | 0.12 | 3.42 | 0.86 | 3.43 | 4.29 | 0.86 | | |
| 0.031 | 0.106 | 0.164 | 0.15 | 3.42 | 0.86 | 3.43 | 4.29 | 0.86 | | |
| 0.031 | 0.106 | 0.190 | 0.09 | 3.42 | 1.00 | 3.97 | 4.61 | 1.00 | 1.08 | **1.08** |
| 0.031 | 0.106 | 0.190 | 0.12 | 3.42 | 1.00 | 3.97 | 4.61 | 1.00 | 0.99 | **0.99** |
| 0.031 | 0.106 | 0.190 | 0.15 | 3.42 | 1.00 | 3.97 | 4.61 | 1.00 | 1.01 | **1.01** |
| 0.031 | 0.106 | 0.216 | 0.09 | 3.42 | 1.14 | 4.51 | 4.92 | 1.14 | 1.22 | **1.08** |
| 0.031 | 0.106 | 0.216 | 0.12 | 3.42 | 1.14 | 4.51 | 4.92 | 1.14 | 1.18 | **1.04** |
| 0.031 | 0.106 | 0.216 | 0.15 | 3.42 | 1.14 | 4.51 | 4.92 | 1.14 | 1.08 | **0.95** |
| 0.031 | 0.106 | 0.240 | 0.00 | 3.42 | 1.26 | 5.01 | 5.18 | 1.26 | 1.44 | **1.14** |
| 0.031 | 0.106 | 0.240 | 0.09 | 3.42 | 1.26 | 5.01 | 5.18 | 1.26 | 1.19 | **0.95** |
| 0.031 | 0.106 | 0.240 | 0.12 | 3.42 | 1.26 | 5.01 | 5.18 | 1.26 | 1.11 | **0.88** |
| 0.031 | 0.106 | 0.240 | 0.15 | 3.42 | 1.26 | 5.01 | 5.18 | 1.26 | 1.05 | **0.83** |

**Table C5. Comparison of Test Results for 18x18 Series to North American Specification**

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0445 | 0.0445 | 0.164 | 0.00 | 1.00 | 1.14 | 1.14 | 0.92 | 0.92 | 1.00 | **1.08** |
| 0.0445 | 0.0445 | 0.164 | 0.09 | 1.00 | 1.14 | 1.14 | 0.92 | 0.92 | 0.85 | **0.92** |
| 0.0445 | 0.0445 | 0.164 | 0.12 | 1.00 | 1.14 | 1.14 | 0.92 | 0.92 | 0.80 | **0.87** |
| 0.0445 | 0.0445 | 0.164 | 0.15 | 1.00 | 1.14 | 1.14 | 0.92 | 0.92 | | |
| 0.0445 | 0.0445 | 0.190 | 0.09 | 1.00 | 1.32 | 1.32 | 0.99 | 0.99 | 0.82 | **0.83** |
| 0.0445 | 0.0445 | 0.190 | 0.12 | 1.00 | 1.32 | 1.32 | 0.99 | 0.99 | 0.69 | **0.69** |
| 0.0445 | 0.0445 | 0.190 | 0.15 | 1.00 | 1.32 | 1.32 | 0.99 | 0.99 | 0.66 | **0.66** |
| 0.0445 | 0.0445 | 0.216 | 0.09 | 1.00 | 1.50 | 1.50 | 1.06 | 1.06 | 0.91 | **0.86** |
| 0.0445 | 0.0445 | 0.216 | 0.12 | 1.00 | 1.50 | 1.50 | 1.06 | 1.06 | 0.84 | **0.80** |
| 0.0445 | 0.0445 | 0.216 | 0.15 | 1.00 | 1.50 | 1.50 | 1.06 | 1.06 | 0.71 | **0.67** |
| 0.0445 | 0.0445 | 0.240 | 0.00 | 1.00 | 1.66 | 1.66 | 1.11 | 1.11 | 1.14 | **1.02** |
| 0.0445 | 0.0445 | 0.240 | 0.09 | 1.00 | 1.66 | 1.66 | 1.11 | 1.11 | 0.88 | **0.79** |
| 0.0445 | 0.0445 | 0.240 | 0.12 | 1.00 | 1.66 | 1.66 | 1.11 | 1.11 | 0.91 | **0.82** |
| 0.0445 | 0.0445 | 0.240 | 0.15 | 1.00 | 1.66 | 1.66 | 1.11 | 1.11 | 0.79 | **0.71** |

**Table C6. Comparison of Test Results for 18x12 Series to North American Specification**

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0445 | 0.1175 | 0.164 | 0.00 | 2.64 | 1.14 | 2.85 | 3.75 | 1.14 | | |
| 0.0445 | 0.1175 | 0.164 | 0.09 | 2.64 | 1.14 | 2.85 | 3.75 | 1.14 | | |
| 0.0445 | 0.1175 | 0.164 | 0.12 | 2.64 | 1.14 | 2.85 | 3.75 | 1.14 | | |
| 0.0445 | 0.1175 | 0.164 | 0.15 | 2.64 | 1.14 | 2.85 | 3.75 | 1.14 | | |
| 0.0445 | 0.1175 | 0.190 | 0.09 | 2.64 | 1.32 | 3.30 | 4.03 | 1.32 | 1.60 | **1.21** |
| 0.0445 | 0.1175 | 0.190 | 0.12 | 2.64 | 1.32 | 3.30 | 4.03 | 1.32 | 1.54 | **1.17** |
| 0.0445 | 0.1175 | 0.190 | 0.15 | 2.64 | 1.32 | 3.30 | 4.03 | 1.32 | 1.54 | **1.17** |
| 0.0445 | 0.1175 | 0.216 | 0.09 | 2.64 | 1.50 | 3.75 | 4.30 | 1.50 | 1.71 | **1.14** |
| 0.0445 | 0.1175 | 0.216 | 0.12 | 2.64 | 1.50 | 3.75 | 4.30 | 1.50 | 1.62 | **1.09** |
| 0.0445 | 0.1175 | 0.216 | 0.15 | 2.64 | 1.50 | 3.75 | 4.30 | 1.50 | 1.68 | **1.12** |
| 0.0445 | 0.1175 | 0.240 | 0.00 | 2.64 | 1.66 | 4.16 | 4.53 | 1.66 | 2.12 | **1.28** |
| 0.0445 | 0.1175 | 0.240 | 0.09 | 2.64 | 1.66 | 4.16 | 4.53 | 1.66 | 1.83 | **1.10** |
| 0.0445 | 0.1175 | 0.240 | 0.12 | 2.64 | 1.66 | 4.16 | 4.53 | 1.66 | 1.71 | **1.03** |
| 0.0445 | 0.1175 | 0.240 | 0.15 | 2.64 | 1.66 | 4.16 | 4.53 | 1.66 | 1.66 | **0.99** |

### Table C7. Comparison of Test Results for 16x16 Series to North American Specification

| $t_1$ (in) | $t_2$ (in) | Screw Diameter (in) | Gap (in) | $t_2/t_1$ | $2.7t_1dF_{u1}$ (kips) | $2.7t_2dF_{u2}$ (kips) | $4.2(t_2^3d)^{1/2}F_{u2}$ (kips) | $P_{cal}$ (kips) | $P_{test}$ (kips) | $P_{test}/P_{cal}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0565 | 0.0565 | 0.164 | 0.00 | 1.00 | 1.10 | 1.10 | 1.00 | 1.00 | 1.07 | **1.07** |
| 0.0565 | 0.0565 | 0.164 | 0.09 | 1.00 | 1.10 | 1.10 | 1.00 | 1.00 | 0.86 | **0.86** |
| 0.0565 | 0.0565 | 0.164 | 0.12 | 1.00 | 1.10 | 1.10 | 1.00 | 1.00 | 0.82 | **0.82** |
| 0.0565 | 0.0565 | 0.164 | 0.15 | 1.00 | 1.10 | 1.10 | 1.00 | 1.00 | | |
| 0.0565 | 0.0565 | 0.190 | 0.09 | 1.00 | 1.27 | 1.27 | 1.08 | 1.08 | 0.86 | **0.80** |
| 0.0565 | 0.0565 | 0.190 | 0.12 | 1.00 | 1.27 | 1.27 | 1.08 | 1.08 | 0.85 | **0.78** |
| 0.0565 | 0.0565 | 0.190 | 0.15 | 1.00 | 1.27 | 1.27 | 1.08 | 1.08 | | |
| 0.0565 | 0.0565 | 0.216 | 0.09 | 1.00 | 1.45 | 1.45 | 1.15 | 1.15 | 0.97 | **0.85** |
| 0.0565 | 0.0565 | 0.216 | 0.12 | 1.00 | 1.45 | 1.45 | 1.15 | 1.15 | 0.92 | **0.80** |
| 0.0565 | 0.0565 | 0.216 | 0.15 | 1.00 | 1.45 | 1.45 | 1.15 | 1.15 | 0.85 | **0.74** |
| 0.0565 | 0.0565 | 0.240 | 0.00 | 1.00 | 1.61 | 1.61 | 1.21 | 1.21 | 1.23 | **1.01** |
| 0.0565 | 0.0565 | 0.240 | 0.09 | 1.00 | 1.61 | 1.61 | 1.21 | 1.21 | 1.11 | **0.92** |
| 0.0565 | 0.0565 | 0.240 | 0.12 | 1.00 | 1.61 | 1.61 | 1.21 | 1.21 | 1.12 | **0.92** |
| 0.0565 | 0.0565 | 0.240 | 0.15 | 1.00 | 1.61 | 1.61 | 1.21 | 1.21 | 0.97 | **0.80** |