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ABSTRACT

Several thousand tests throughout the world have been conducted on the shear strength of screw connections in cold-formed steel, however, little to no research has been conducted on how various thicknesses of insulation placed between two sheets of steel, such as a steel panel and structural supporting member, affects a screw's shear strength. Elemental tests were conducted as part of this study at Virginia Tech where rolled fiberglass insulation was placed between two pieces of steel connected by self-drilling screws and tested to failure. The results were compared to the North American Specification for the Design of Cold-Formed Steel Structural Members to determine if the presence of insulation affected the shear and tensile strengths of screw connections involving insulation.

While the presence of insulation between two steel sheets connected by screws does reduce the shear strength of the connection, the current equations for predicting this strength in the North American Specification are adequate. When the data acquired from this study and the screw shear data obtained in past research were combined, it was clear that the data collected during this study fell within the scatter of the data used to develop Section E4.3 of the North American Specification. The results of the elemental tests and subsequent analytical comparisons will be presented in this paper.

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INTRODUCTION

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).

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

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

$$P_{ns} = 2.7\, t_1 d\, F_{u1} \quad (1.2)$$

$$P_{ns} = 2.7\, t_2 d\, F_{u2} \quad (1.3)$$

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

$$P_{ns} = 2.7\, t_1 d\, F_{u1} \quad (1.4)$$

$$P_{ns} = 2.7\, t_2 d\, F_{u2} \quad (1.5)$$

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

Development of Specification

European recommendations were used as a basis to derive provisions for the North American Specification. In a study by 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:

for $t_2 / t_1 = 1.0$ the smaller of

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

$$P_{ns} = 2.1\, t_1 d\, F_y \quad (1.7)$$

for $t_2 / t_1 \geq 2.5$

$$P_{ns} = 2.1\, t_1 d\, F_y \quad (1.8)$$

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 can be used with any consistent system of units.

The above equations account for the limit states of tilting and subsequent pull-out of the screw, and bearing of the metal plates. Screw shear is evaluated separately and is based on data developed by and available from manufacturers.

Three 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 a result of the influence of the first two modifications on the determination of the resistance facor.

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 may or may 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.

Review of Past Research

The most common application for the results of this research project will be roof systems in metal buildings. Past 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 provides the current strength equations (these are shown as Eqs 1.1-1.5 in the INTRODUCTION of this paper), which were developed by Pekoz (1990.) All elemental tests conducted for this project were compared to these equations..

The paper presented by Pekoz (1990) was a revision of an earlier report also written by Pekoz (1989). Pekoz did not perform additional tests for the specification developement, but instead he used data from four other studies. The data in these studies were compared to the European Recommendations and in turn, appropriate changes were proposed to AISI.

The first set of data used by Pekoz was from the Illinois Tool Works (Janusz, et al as referenced in 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. (0.5 mm) to 0.188 in. (5 mm) steel sheet. All screws were hex washer head TEKS. The ultimate strength of the material and maximum test load were noted, however the mode of failure was not reported. 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.

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. (0.6 mm) to 0.060 in. (1.5 mm) steel sheet. As in the previous reference, screw shear did occur when relatively thick steel sheets were used. These were noted and not included in the development of the equations. Both yield and ultimate strengths for the steel were reported.

The third source of screw shear data was from a report to the Swedish Building Research Institute (Berggren and Baehre 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. (0.7 mm) to 0.200 in. (5 mm) 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 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. (0.5 mm) to 0.100 in. (2.5 mm) 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 from all the studies were presented by Pekoz (1990) in plots similar to Fig 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.

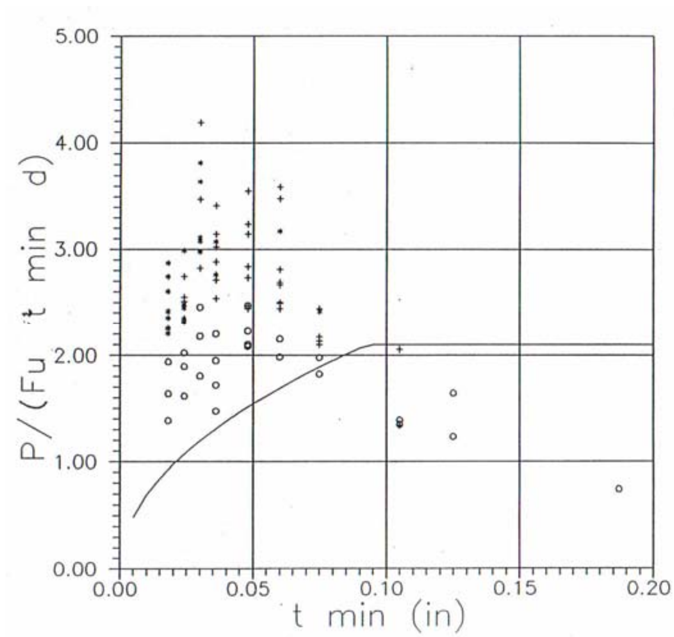

Figure 1 Sample of Test Results (*Pekoz, 1989*)

Objective

The objective of the work presented herein is two 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, which simulate a steel deck and supporting structural member, such as a cold-formed purlin. The second objective is to determine if modifications to Section E4.3 of the North American Specification for the Design of Cold-Formed Steel Members (*North American* 2001) are needed.

Elemental Tests - 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 and 20 standard lap-joint 2 screw shear tests using vinyl faced insulation.

Coupon Tests

Tensile coupon tests were conducted on three specimens from each steel sheet stock that was used. The specimens were machined to the following nominal dimensions:
Length: 8 in. (20.3 mm) Width: ¾ in. (19 mm) Milled Width: ½ in. (13 mm) 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 (133 kN) load cell in an INSTRON Model 4206-006 screw operated testing machine. Tests were preformed at a speed of 0.1 in./min (2.5 mm/min) until failure. A summary of the tensile coupon test results are given in Table 1.

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. 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 measured. The distance measured was from the bottom of the lower sheet to the top of the upper sheet adjacent to the location that 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 determine the thickness 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 summarized in Table 2.

Table 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**

1 in. = 25.4 mm, 1 ksi = 6.895 MPa

Table 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

1 in. = 25.4 mm

The diameters of the different size screws used during the element tests were measured and are presented is Table 3.

Table 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

1 in. = 25.4 mm

Shear Test Details - 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* 2003). Figure 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. 3. The recommended geometric proportions of each specimen were followed except for width and length (*Cold-Formed* 2003). The width was reduced from the recommended 2 3/8 in. (60 mm) to 2 in. (51 mm) so that the specimen would fit into a 2 in. (51 mm) 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. Elemental Test

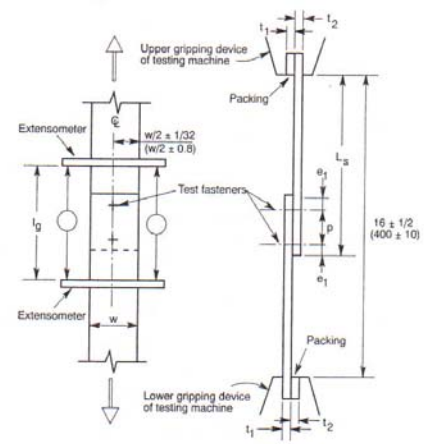

Figure 3. Elemental Test Setup (*Cold-Formed*, 2003)

The dimensions used for each specimen were:

w = 2 in. (51 mm)
L_s = 12 in. (305 mm)
e_1 = 1 3/16 in. (30 mm)
p = 2 3/8 in. (60 mm)
l_g = 10 in. (254 mm)
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./min (5 to 8 mm/min) 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. (1.6 mm). Five repetitions of each configuration were conducted.

Test Parameters

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. (3 mm) to 0.019 in. (0.5 mm) steel sheet, 0 to 6 3/8 in. (0 to 162 mm) of unfaced fiberglass insulation, and #8 to #14 screws. A detailed test matrix is given in Lease and Easterling (2006).

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.; 0, 83, 108, 162 mm) 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 influence the impact of insulation on the shear strength of screw connections in metal deck. Material ranged in thickness from 0.023 to 0.057 in. (0.6 to 1.5 mm) sheet stelel, 3 to 6 in. (76 to 152 mm) of faced insulation, and #12 and #14 screws.

Shear Test Results

The detailed data obtained from the 455 elemental tests using unfaced insulation and vinyl faced insulation are presented in Lease and Easterling (2006.) 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. Any test that failed by screw shear was not included in the comparisons that follow.

Data Analysis and Comparison to Proposed Models

Data Analysis

The results from the elemental tests will be examined to determine if modifications to the North American Specification are necessary to account for the presence of insulation. 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 are given as Eqs 1.1-1.5 of this paper.

Comparisons to Section E4.3 of the North American Specification (2001) can be viewed in Lease and Easterling (2006.) The results contained in the report include 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 and 5, respectively. Each symbol in the two figures represents the average of the five tests for each configuration. The ratio of the test mean to the calculated mean for all elemental tests using unfaced insulation is 1.00 and the standard deviation 0.14.

Most of the tests were conducted with unfaced insulation. During the course of the testing, a question arose as to the influence of using unfaced insulation instead of vinyl faced insulation, which is more common in metal building roof systems. Thus, a series of tests were conducted using vinyl faced insulation.

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. The ratio of the test mean to the calculated mean for the 0.0295 in. x 0.0435 in. (0.75 mm x 1.1 mm) series using 3 in. (76 mm) insulation and #12 and 14 screws is 0.85 and 0.88 and the standard deviation is 0.112 and 0.052, respectively. The ratio of the test mean to the calculated mean for the 0.0565 in. x 0.0565 in. (1.4 mm x 1.4 mm) series and 0.023 in. x 0.058 in. (0.6 mm x 1.5 mm) series using 6 in. (152 mm) insulation and #14 screws was 0.86 and 0.88, while the standard deviation was 0.112 and 0.113, respectively. 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, thus no further distinction is made between the two.

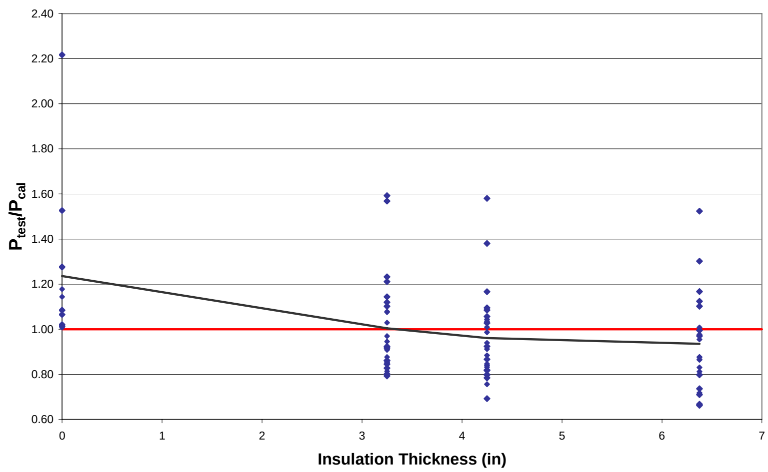

Figure 4. Strength vs Insulation Thickness

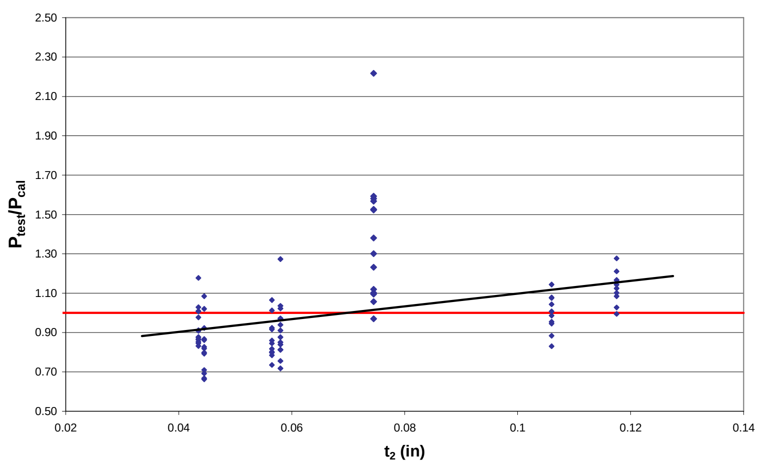

Figure 5. Strength vs t_2

Table 4. Comparison of Tests Using Unfaced vs Vinyl Faced Insulation

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

1 in. = 25.4 mm, 1 kip = 4.448 kN

Modifications to Strength Equations

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 expression 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. 6, 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 the tests using 12 and 14 ga material is 1.19 and the standard deviation is 0.27.

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

Modification 1. 0.85

Modification 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 modifications 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 thinner then nominal 14 gauge were considered. Similar results were found for the two proposed modifications. Given that modification 1 is simpler to apply than modification 2, only modification 1 is considered further herein. The results can be viewed in Table 5.

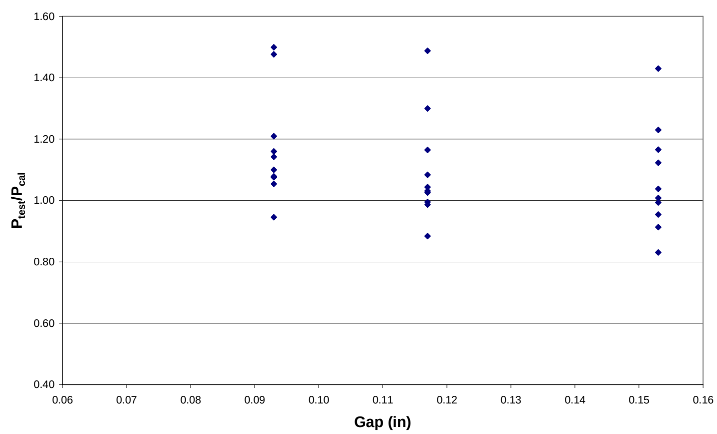

Figure 6. Element Tests Using Nominal 12 and 14 ga Material

Table 5 Comparison of Modifications Excluding 12 and 14 ga Tests

	Current Method	**Modification 1**
	P_{test}/P_{cal}	**$P_{test}/0.85P_{cal}$**
Average	0.85	1.00
Standard Deviation	0.09	0.11

Resistance Factor Analysis

A resistance factor determination based on the elemental screw shear data compared with the current specification and with modification 1 was conducted. Resistance factors and factors of safety for four cases were calculated using the same method used by Pekoz (1990), 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 are given below in Eqs 4.6 and 4.7.

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

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

where:

ϕ	= resistance factor
C_ϕ	= 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
β_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
Ω	= factor of safety

The results of the calculations for the four chosen cases can be viewed in Table 6. 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). This report was fundamental in the development of the current provisions, and included test data with a range of resistance factors from 0.408 to 0.771. Based on these observations, no change in the North American Specification is warranted, even though the data in the present study indicates a decrease in screw strength as a function of insulation thickness. The decreased values are still well within the scatter of the data reported by Pekoz (1990) for screw tests without insulation, as indicated by the results in Table 6.

Table 6. 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

Conclusions

The results of this research project indicated that the shear strength of screws, as calculated with the North American Specification ((2001), was reduced by the presence of insulation between two sheets of steel. However, when these results are considered as part of the larger data base of test results reported by Pekoz (1989), no modifications to the specification equations are warranted. The resistance factors calculated for the tests including insulation and calculations based on the current specification are above those currently used and the factors of safety are lower than those currently used. Thus, the current specification provisions can be used without modification when insulation no greater than 6-3/4 in. (171 mm), before compression, is used.

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