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Determination of the tensile and shear strengths of screws and the effect of screw patterns on cold-formed steel connections

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Civil Engineering Study 98-3
Cold-Formed Steel Series

First Summary Report

DETERMINATION OF THE TENSILE AND SHEAR STRENGTHS OF SCREWS and THE EFFECT OF SCREW PATTERNS ON COLD-FORMED STEEL CONNECTIONS

by

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PREFACE

This report summarizes two studies related to the design of cold-formed steel connections. The study topics included the creation of a test standard for determining the strength of a screw, and the determination of the strength of a screw connection.

A standard test protocol does not exist for determining the strength of a screw. Today, manufacturers use test protocols developed for their products. Thus, there is no consistency in defining the structural performance of a screw. A test standard has been developed. The standard used as its model the American Society of Testing and Material's F 606, *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners and Rivets*. Tests have been conducted to show the practicality of the proposed test standard.

The connection strength equations in the AISI design specification are based primarily on tests of single- and double-screw connection tests. Also, design assumes that the connection strength is proportional to the number of screws. The connection strength study considered the variation of connection strength with the number of screws, the screw center-to-center spacing, and the location of the screws in the connection.

This experimental study demonstrated that connection strength increased with additional screws in the connection, but the increase was at a rate less than a multiple of the single screw strength.

Current design specifications do not account for the pattern formed by the screws in a connection. This study showed that the screw pattern has a minor effect on the structural performance, but may be neglected for the purposes of design.

Finally, this experimental study determined that the connection strength decreased with a decrease in the center-to-center spacing of the screws.

This report is based on a thesis submitted to the Faculty of the Graduate School of the University of Missouri-Rolla in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering.

Technical guidance for this investigation was provided by the American Iron and Steel Institute's Subcommittees on Test Procedures (S. R. Fox, Chairman) and Connections (M. Golvin, Chairman). The Subcommittees' guidance is gratefully acknowledged. Thanks are also extended to H. H. Chen, D. F. Boring, and S. P. Bridgewater, AISI staff, for their assistance. Steel sheet used for the experimental phase of this study was provided by Dietrich Industries.

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1. INTRODUCTION

1.1 GENERAL

Self-drilling screws are externally threaded fasteners which, when driven with a screw gun, drill their own hole and form their own threads in steel sheet. Studies have been performed to develop a standard test for determining both the tensile and the shear strength of screws, and to obtain a better understanding of the strength of cold-formed steel lap connections formed with self-drilling screws in varying numbers and patterns.

1.2 STANDARD TEST

There exists no standard for testing screw strength, as exists for testing bolt strength. For bolts, the standard is ASTM F 606-95b "Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets" (ASTM, 1995). The American Iron and Steel Institute's *Cold-Formed Steel Design Manual* (AISI, 1996) gives design provisions for determining the strength of a screw connection, but gives no guidance on defining the screw tensile and shear capacities. Because of the lack of a test standard for screw strength, manufacturers of screws have devised their own procedures for determining the strength of their own products. This leads to possible inconsistency in strength from one manufacturer to another, and leaves the design engineer with no objective standard by which to compare screws from different manufacturers.

In this study, ASTM F 606-95b (ASTM, 1995) was used as a pattern by which to develop a procedure for testing screws. A literature survey was performed to determine the various test methods used by screw manufacturers. Proposed test procedures were developed and tested to determine their practicality. A written test method was created that is suitable for adoption by the American Iron and Steel Institute and the American Society for Testing and Materials. Procedures were developed for defining screw strength in tension, shear, and combined tension and shear.

1.3 CONNECTION STRENGTH

Screw connection strength equations in the current American Iron and Steel Institute's *Cold-Formed Steel Design Manual* (AISI, 1996) are based on a data base of over 3500 tests. Because the test parameters involved are broad, there is much scatter in the data, and the design equations were consequently conservatively developed.

This study has focused on design parameters typically found in residential construction in the United States. Patterns, spacing, and number of screws were varied to determine their effect on connection strength. Previously, screw patterns and spacing had not been studied extensively. Design equations for establishing the connection strength have been developed.

2. REVIEW OF LITERATURE

2.1 GENERAL

The following sections review literature pertinent to this study. For the standard test, documents investigated include recognized performance standards, manufacturer test procedures, and available literature. For connection strength, referenced documents include the work of Daudet (1996), Rogers and Hancock (1997), and Breyer (1993).

2.2 STANDARD TEST

Listed are various sources that outlined testing procedures already in use for determining the mechanical properties of screws.

2.2.1. Society of Automotive Engineers J78 (SAE, 1979). SAE J78 "Self Drilling Tapping Screws" (SAE, 1979) addresses mechanical requirements for self-drilling screws, as well as dimensional, material, process, and performance requirements. The tests listed in this specification focus on torsional strength, rather than tensile or shear strengths. The main strength test is the Torsional Strength Test (torque required to fail a screw). In this test, the screw threads are clamped such that they are not crushed, and at least two full threads are left exposed above the clamping device. A calibrated device is used to apply torque until failure, the failure torque is called the torsional strength of the screw.

2.2.2. American Society for Testing and Materials F606-95b (ASTM, 1995). The applicable ASTM standard for fasteners is "Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets" (ASTM, 1995). The standard sets forth procedures for determining mechanical properties of threaded fasteners, such as hardness, tension strength, torsion strength, and shear strength. This standard does not apply to screws because the tests pertaining to strength involve the [illegible] of a nut that threads onto the bolt.

2.2.3. <u>MIL-STD-1312-8A (DOD, 1984).</u> The Military Standard "Fastener Test Methods - Method 8, Tensile Strength" addresses tensile strength for any structural fastener, and is therefore broad in scope. Tension test fixtures are recommended. Load rates are specified as a function of the diameter of the fastener to be tested (e.g., a 0.25 inch diameter fastener has a load rate of 5 lb/min). This standard does not apply to screws because the tests pertaining to strength involve the use of a nut that threads onto the bolt.

2.2.4. <u>American Iron and Steel Institute (AISI, 1996b).</u> The American Iron and Steel Institute's document, "Test Methods for Mechanically Fastened Cold-Formed Steel Connections" (AISI, 1996b) outlines a lap-joint shear test. The shear test involves lapping two sheets together and connecting them with a self-drilling screw. The assembly is put into a tension testing machine and a uniaxial tension force is applied. Various tension tests are also specified for determining pull-over and pull-out of a screw. However, the test method does not provide guidance for determining the tension or shear strength of a screw.

2.2.5. <u>Manufacturers' Test Methods.</u> Test procedure information was provided by several manufacturers. The previously mentioned documents SAE J78 (SAE, 1979), ASTM F606 (ASTM, 1995), or the AISI "Test Methods for Mechanically Fastened Cold-Formed Steel Connections" (AISI, 1996) were often cited as references by manufacturers.

ITW Buildex's standard is titled, "Work Instruction QWI 10.6 - Lab Instructions for Mechanical Properties Testing of Buildex Fasteners" (ITW Buildex, 1995). Buildex specifies its own fixtures and testing rate. Referenced tests include: pull-out, shear, pull-over, torsion, and tension. The tension test includes a bottom plate that the screw threads are driven or threaded into, and a top fixture that allows the screw head to bear against it. The assembly is placed into a tension testing machine and the screw is tested to failure. The shear test consists of two test plates that are lapped, the screw is driven through the plates, and the assembly is placed into a tension testing machine and the screw is tested to failure.

Another manufacturer standard was provided by Vicwest titled "Vicwest Fasteners Manual" (Sommerstein, 1996). This standard included fixtures for testing pull-over, pull-out, and shear strength of screws. The shear test involved lapping two sheets of steel and connecting them with a self-drilling screw. The screw is tested to failure in a tension testing machine. No tension test was given.

2.2.6. Luttrell (1996). Luttrell wrote a preliminary, unpublished report called, "Deck Attachment with No. 12 Screws Under Combined Loading" (Luttrell, 1996). His study focused on screws attaching deck sections in uplift situations. In such situations the fastener experiences combined tension and shear forces. A test frame was devised that involved attaching a piece of steel deck to a steel channel section, and loading the assembly at an angle to achieve combined tension and shear through the connector.

2.2.7 Yu (1991). Yu's textbook gives a good overview of the behavior of bolted connections, which is a good background to understanding screwed connection behavior.

Failure modes are defined, which include longitudinal shear failure of the sheet, bearing failure of the sheet, tensile failure of the sheet, and shear failure of the bolt.

2.3 CONNECTION STRENGTH

The references listed below present information on screw and bolted connection strength.

2.3.1. Daudet (1996). Daudet's work is summarized in his Master's Thesis, titled, "Self-Drilling Screw Connections in Low Ductility Light Gage Steel" (Daudet, 1996). Daudet investigated double-lap and single-lap shear connections that used self-drilling screws. The steel used in the study included both normal and low ductility sheets. The failure modes that were investigated included edge tearing, bearing, tilting/bearing, and screw shear. The test results were used to create design equations.

Daudet studied both single- and two-screw connections. In the study, a decrease in strength per screw, as much as 14%, was found for two-screw connections as compared to single-screw connections. Daudet hypothesized two reasons for this behavior. The first was that lifting of screws was observed when two screws were placed parallel to the loading direction, which increased the load eccentricity on the screws. The second reason was possible misplacement of screws, moving the center of gravity of the connection away from the center of gravity of the connected sheets.

2.3.2. Rogers and Hancock (1997). Rogers and Hancock's work is summarized in their report "Screwed Connection Tests of Thin G550 and G300 Sheet Steels" (Rogers and Hancock, 1997). Single-lap connections were investigated for different thicknesses of steel sheet with either two- or four-screw patterns. Failure modes investigated included bearing, tilting, and bearing/tilting. The effect of anisotropy was also considered by milling test sheets from the parent material longitudinally, transversely, and diagonally.

2.3.3. Breyer (1993). In timber design, the concept of a "group action factor" is used to account for the fact that in a connection with multiple bolts, the bolts at the ends of a longitudinal line carry more load per bolt than the intermediate bolts (Breyer, 1993). The "group action factor" reduces the connection strength, and is predominantly a function of the number of fasteners in a line parallel to the direction of loading. Lesser factors include stiffness ratio of members being joined, fastener diameter, fastener spacing parallel to direction of force, and the fastener load/slip modulus.

2.3.4. American Iron and Steel Institute (AISI, 1996a). The American Iron and Steel Institute's document, "Specification for the Design of Cold-Formed Steel Structural Members" (AISI, 1996a), outlines current design equations for connections made with screws. The equations for connection shear, with the two steel sheets joined being the same thickness, is taken as the smaller of equations (2-1) and (2-2).

$$P_{ns} = 4.2\sqrt{t^3 d}F_u \tag{2-1}$$

$$P_{ns} = 2.7tdF_u \tag{2-2}$$

P_{ns} = nominal shear strength per screw

t = thickness of steel sheet

d = nominal screw diameter

F_u = tensile strength of steel sheet

3. TENSILE AND SHEAR STRENGTH OF SCREWS

3.1 GENERAL

The research to establish a standard test method for determining the screw strength involved defining test procedure concepts and validating the concepts for practicality and reliability. A total of 28 tension tests, 16 shear tests, 24 torsion tests, and 4 combined shear and tension tests were performed. The different fixtures and test methods that were tried, and which were deemed to be most practical, are discussed herein. The proposed test protocol, "Standard Test Methods for Determining the Mechanical Properties of Screws", is given in Appendix A. Appendix B contains details for test fixtures that were fabricated as part of this research. Test results and parameters are listed in Appendix C.

The proposed standard test for self-drilling screws was modeled after ASTM F606 (ASTM, 1995), and focuses on the tension test. The product hardness and proof load tests were not adopted, as well as ASTM F606 information on internally threaded fasteners, washers, and rivets. Also, tension testing of machined test specimens was not adopted because screws are typically not large enough to have specimens machined from them. Wedge tension testing was adopted in a modified form as a combined tension and shear test. ASTM F606's testing speed, the greater of 0.1 in (2.5 mm) per minute or 500 pounds (approximately 2 kN) per minute, was followed.

A correlation between product hardness and tensile strength was considered, but rejected. Correlation between hardness and ultimate tensile strength can be found in ASTM A370 (ASTM,1997). However, due to case hardening of the screw, its cross-section contains a variation in hardness. Thus it is difficult to assign a single hardness value that can then be used to correlate to a screw's tensile strength. Micro-hardness testing would have had to be performed, and considering the small cross-section of a screw, and because the micro-hardness testing apparatus is not readily available to most manufacturers, hardness testing was not included in the proposed screw test standard.

The shear test method was adopted from the American Iron and Steel Institute's document "Test Methods for Mechanically Fastened Cold-Formed Steel Connections" (AISI, 1996b). The report protocol was adopted from this document as well.

3.2 UNIAXIAL TENSION TEST

Two test methods were examined for determining the tensile strength of a screw. One method involved a two-piece fixture designed to hold the screw, with one piece holding the head, and the other holding the threads. The other test method, in which the threads of the screw are clamped in the hydraulic grips of the testing machine, eliminates the need for the bottom fixture. The testing machine used was a Materials Test System (MTS) 880 (Figure 3.1). Electronic data acquisition was employed, and the maximum applied load was recorded as the strength of the screw.

The test fixture and setup using the two-piece fixture may be seen in Figure 3.2, with a photo given in Figure 3.3. The fixtures' dimensions are given by Figures B.1 and B.2 in Appendix B. The fixtures were made from mild steel. The disadvantage of this design was that for each screw thread size and type, a unique bottom fixture needed to be fabricated. The top fixture had a hole just large enough to allow the screw threads to pass through. This maximized the bearing area for the screw head. The top fixture was clamped in the jaws of the tension testing machine. The bottom fixture was threaded

Figure 3.1 Photo of Materials Test System 880 Tension Testing Machine

onto the thread end of the screw, with a minimum of four threads left exposed between the top and bottom fixtures. The bottom fixture was also clamped in the jaws of the tension testing machine. The assembly was subjected to a uniaxial tension force until the screw fractured into two pieces.

The alternate tension test method involved clamping the threads directly in the tension testing machine's jaws. The tension testing machine used had textured jaw surfaces that allowed good gripping of the screw threads, and conservative test results were obtained. Premature failure may occur if care is not taken to prevent crushing of the screw threads. A comparison of tension tests with and without the use of the bottom fixture are given in Table 3.1. The average strength with the bottom fixture is 3926 lbs. and without the bottom fixture it is 3793 lbs, which gives a conservative 3.5 % difference.

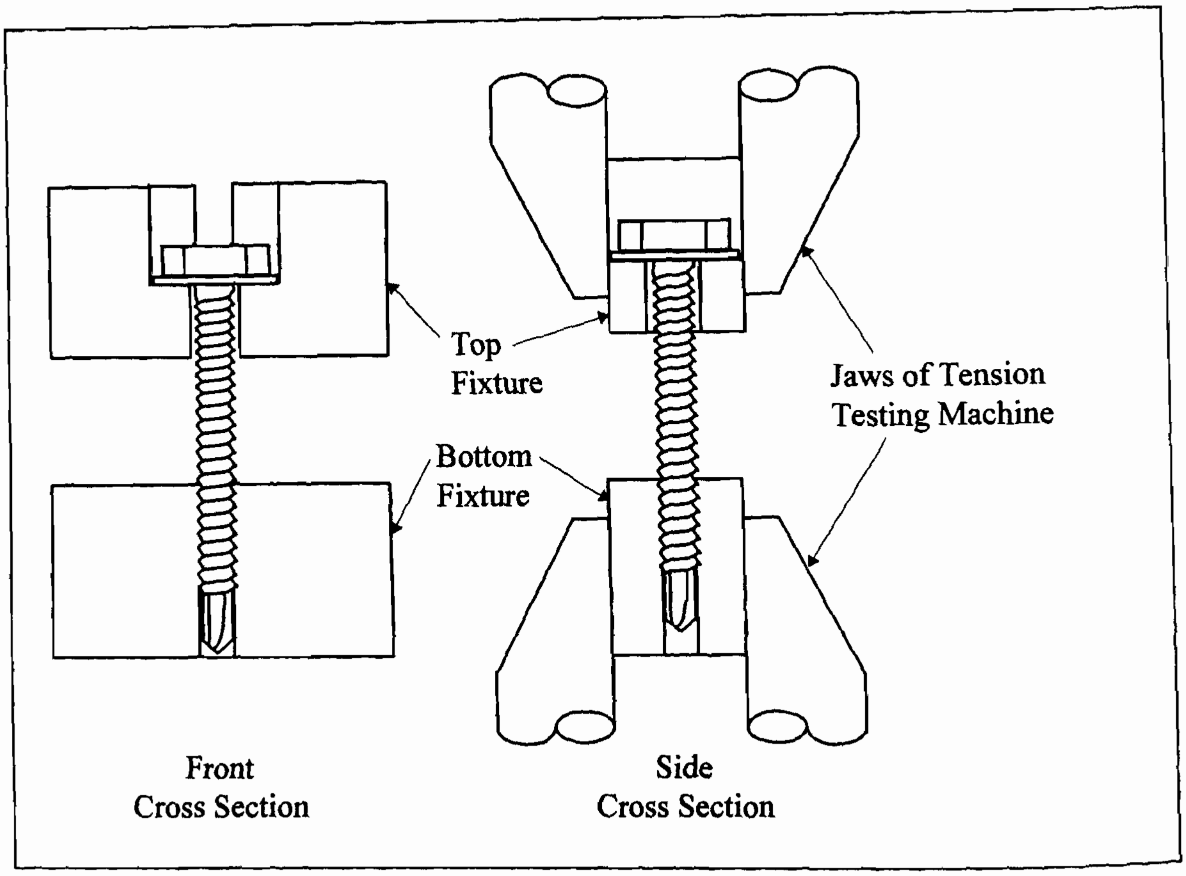

Figure 3.2 Cross Section of the Tension Test Setup

Table 3.1 Tension Tests With and Without Bottom Fixture

Test #	Failure Load (lbs)	Using Bottom Fixture?
t23	3966	Y
t24	3886	Y
t26	3837	N
t27	3664	N
t28	3878	N

Note: #10-16x1-1/2" Traxx hex head screws.

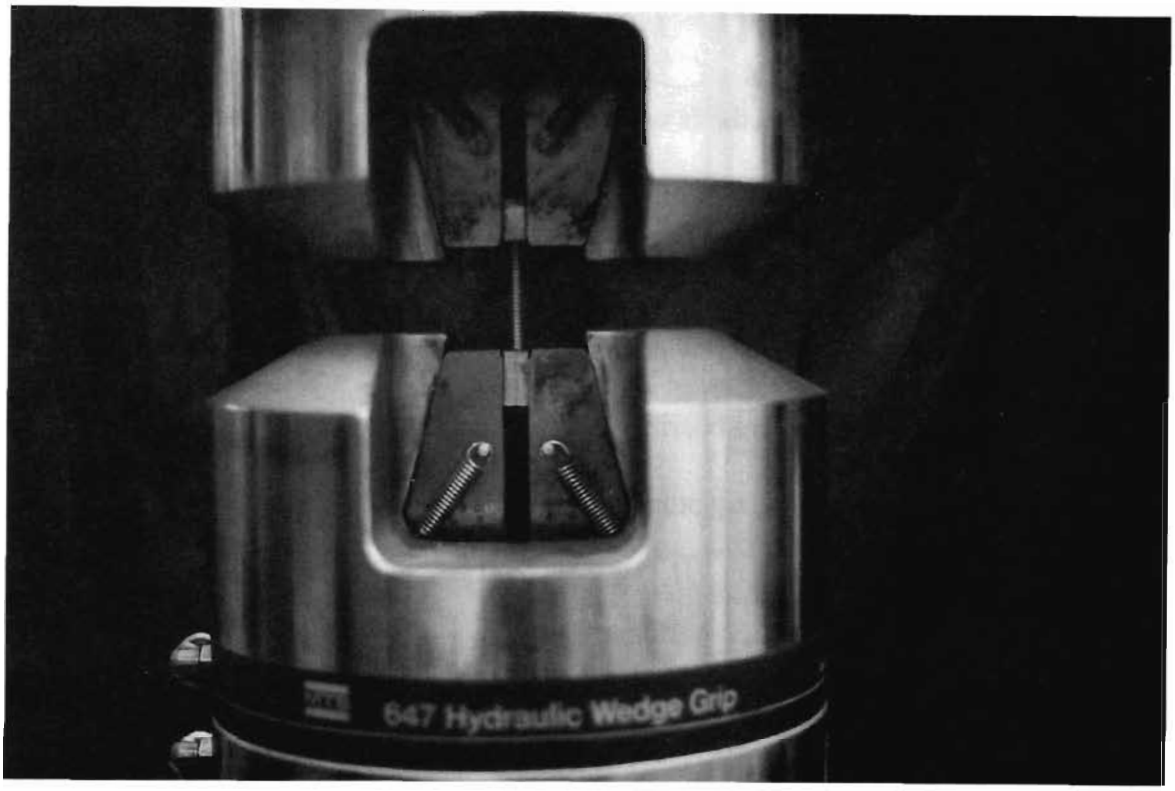

Figure 3.3 Photo of Tension Test Setup

A load rate was selected, as determined by the rate of separation of the testing machine heads, limited to the greater of 0.1 in/min (2.5 mm/min) or the rate caused by a loading rate of 500 pounds/min (approximately 2 kN/min). This load rate is consistent with the procedures prescribed by ASTM F 606-95b "Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets" (ASTM, 1995). Stroke control was used during the experimental study because it allowed the machine heads to be stationary during setup. No attempt was made to create a tensile strength design equation based on these tests. The sole purpose of conducting the tests was to verify that the test method was reliable and consistent, as well as easily applied.

3.3 SHEAR

Two different test methods were used for testing screws in shear. One method involved a two-piece fixture (Figures 3.4 and 3.5) that had a pre-drilled hole into which the screw was inserted. The fixture dimensions are given by Figure B.3 in Appendix B. In the other test method, the screw drilled its own hole into two steel sheets that were of sufficient thickness to prevent bearing failure of the sheet. This was to ensure that the screw failed in shear before any other mode of failure could occur.

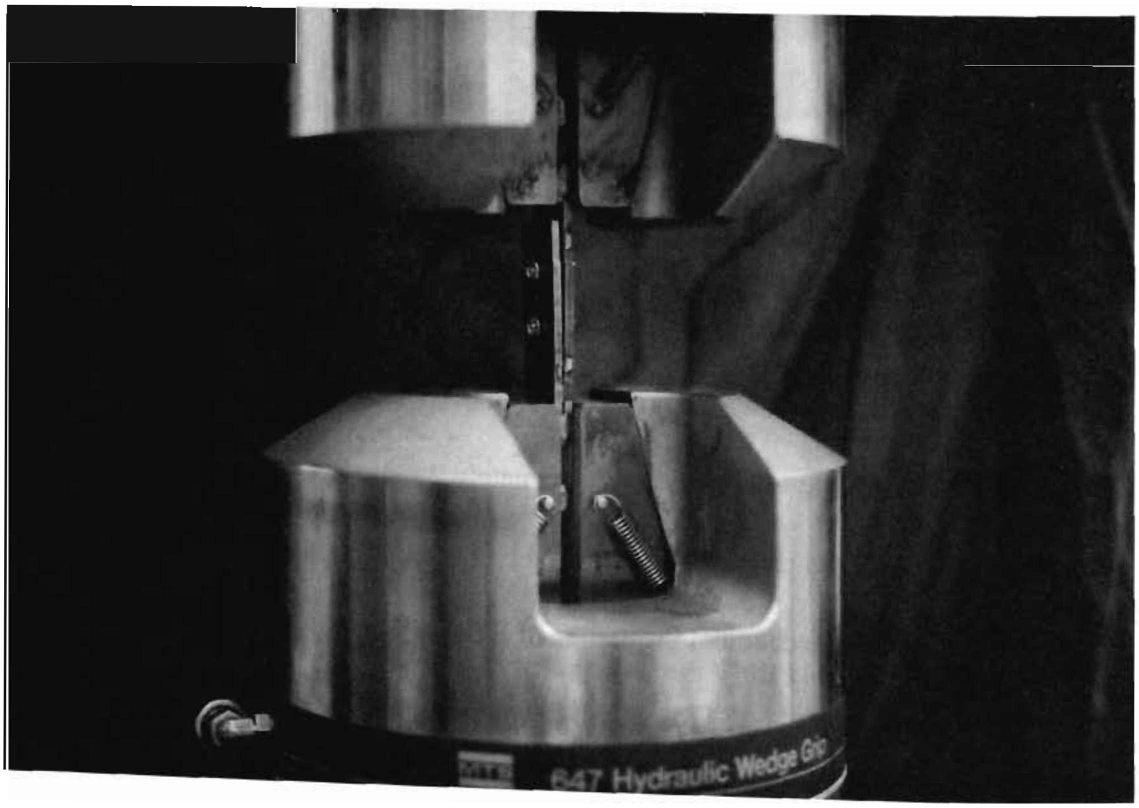

Figure 3.4 Photo of Shear Test Setup Fixtures

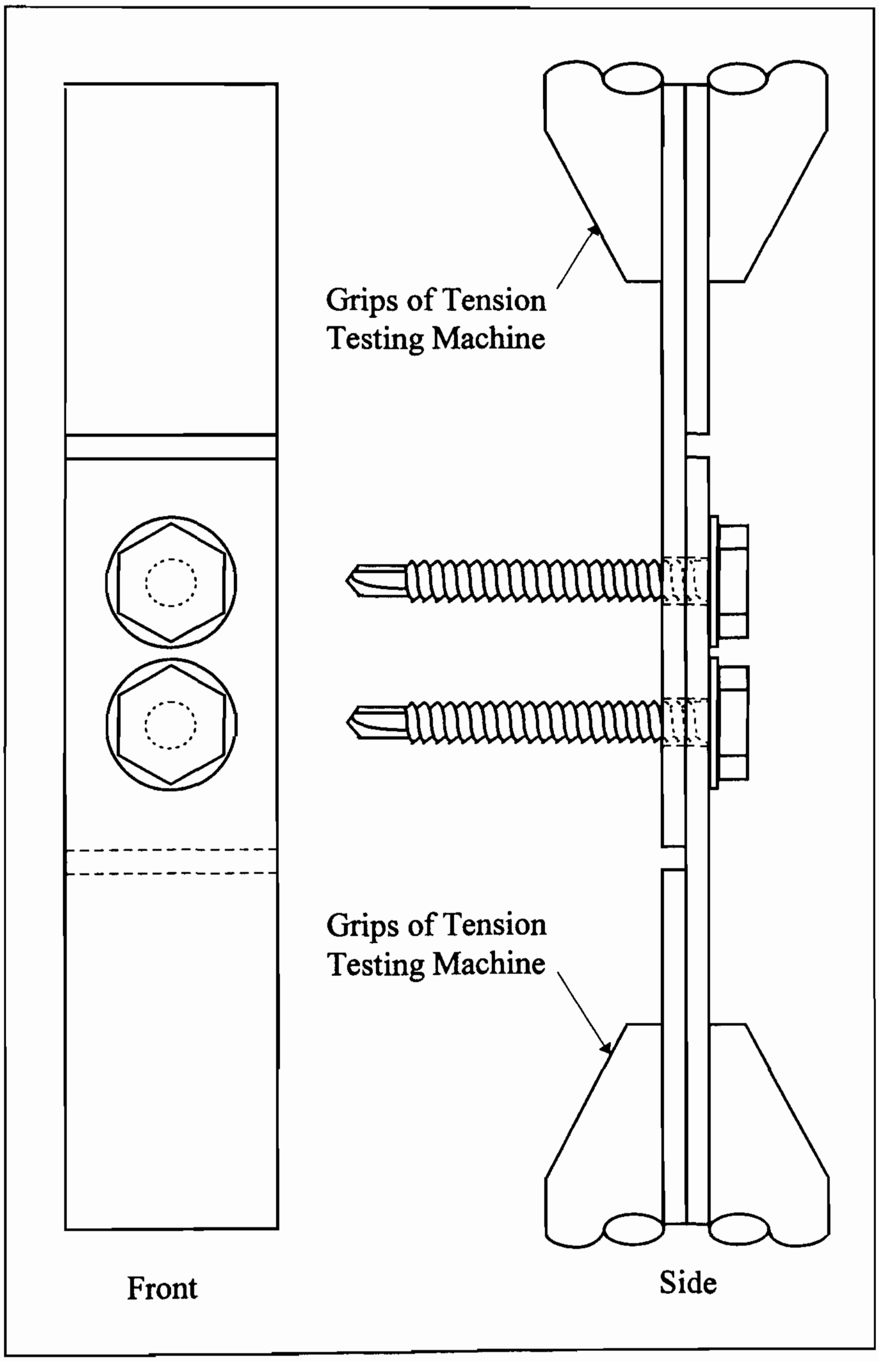

Figure 3.5 Shear Test Setup Fixtures

One problem with the test fixture of Figure 3.5 was that the screw tilted during the test (Figure 3.6), so that the screw actually experienced combined tension, shear, and bending. This was possible because the holes in the fixture were just large enough to allow the screw threads to pass through without engagement. Typically, screw tilting reached as much as 30 degrees from the horizontal during testing, and the plates separated as much as 1/8" before failure of the screw (Figure 3.6). The tilting occurred very early in the test, before much load was applied. At failure the screw would break into three pieces (Figure 3.7), with the middle piece becoming larger as more permanent bend was introduced into the test fixtures.

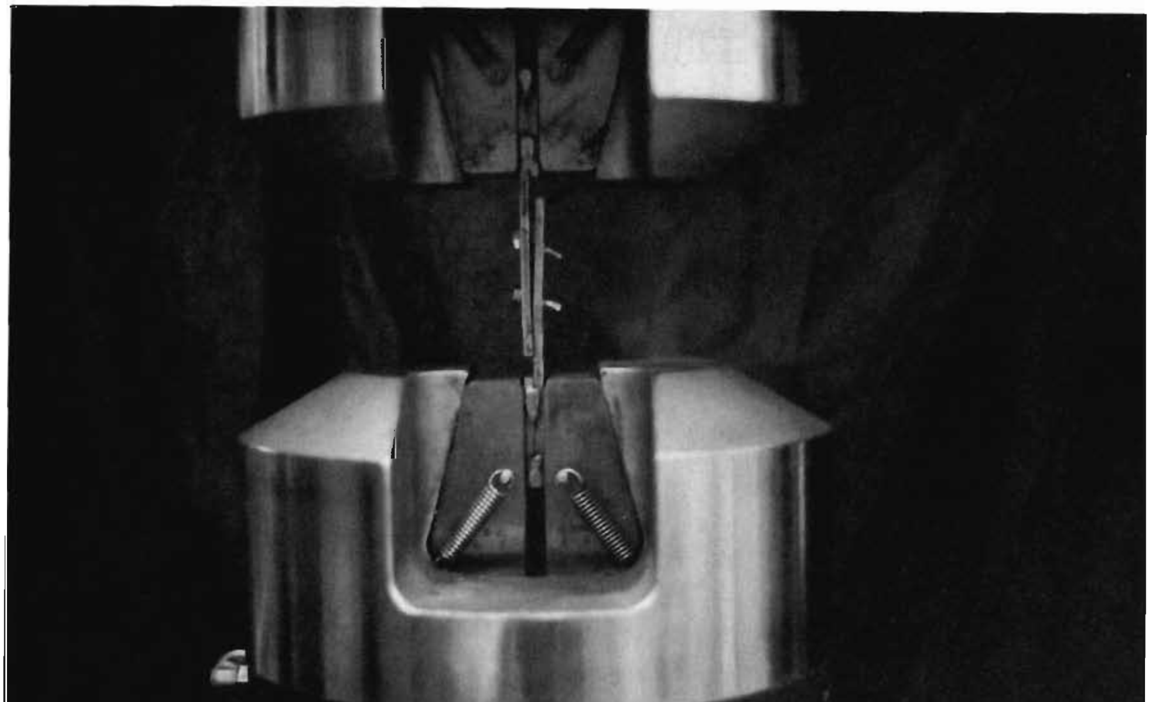

Figure 3.6 Screw Tilting and Plate Separation During Shear Test

Screws were tested using the test fixture of Figure 3.5 in several combinations (Figure 3.8). A single screw was tested, both with the head flush against the fixture face

(Figure 3.8 - #1) and backed out from the face enough to prevent the head from touching the face during the test (about 1/4" - Figure 3.8 - #2). Two screws were tested flush against the face, inserted the same direction (Figure 3.8 - #3) and inserted in opposite directions (Figure 3.8 - #4). Two screws were also tested backed away from the face of the fixture, inserted the same direction (Figure 3.8 - #5). Test results are given in Table 3.2.

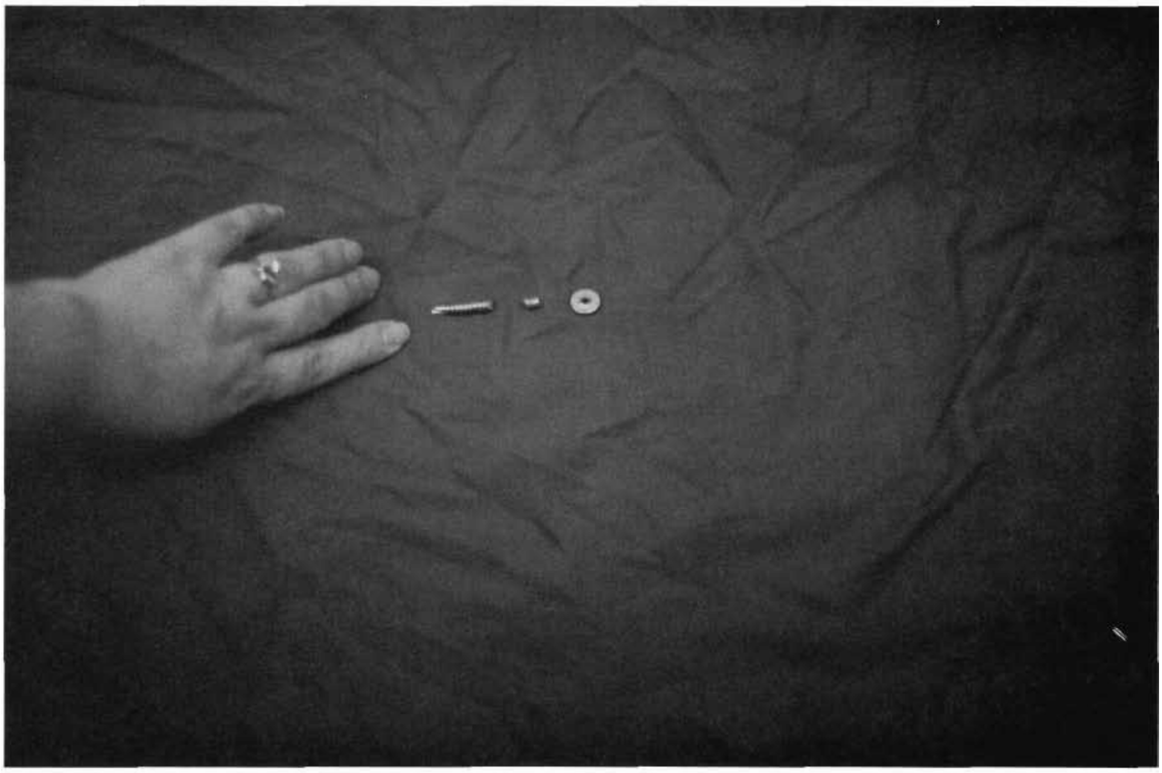

Figure 3.7 Screw Breakage During Shear Test

Testing two screws instead of a single screw did not yield twice the strength when the screws were flush against the face of the fixture. One screw would hold the majority of the load until it failed, then the remaining screw would take the load. This resulted in two distinct peak loads during testing double screws flush against the fixture face. When two screws were backed away from the fixture face, they tended to act in unison and the connection achieved near twice the strength of a single screw test. Statics would say that each screw in both cases should have seen the same load. The difference in behavior of the two screw tests may be due to experimental error and slight deviations in the screw cross section and material properties.

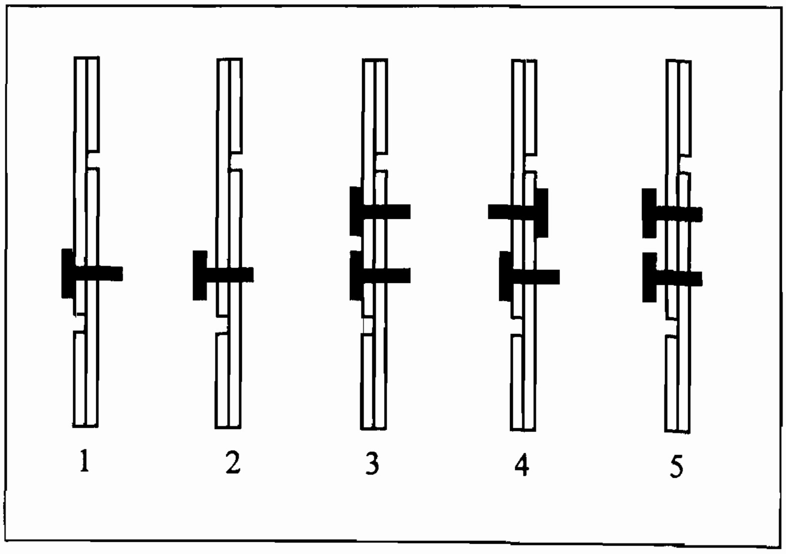

Figure 3.8 Screw Positions for Shear Testing

Thus the logical testing procedure, which used two steel sheets joined together by the screws to be tested (Figures 3.9 and 3.10) was determined to be the best test fixture. The advantage of this was that the screw was placed into the sheets in the same manner that it would be used in a real connection, i.e. it drilled its own hole and tapped its own threads. This more accurately simulated the actual condition in the field. As long as the sheet thickness was adequate to prevent a tilting or bearing failure of the screw, the screw failed in shear. Screw spacing and edge distance were selected to prevent tearout failures.

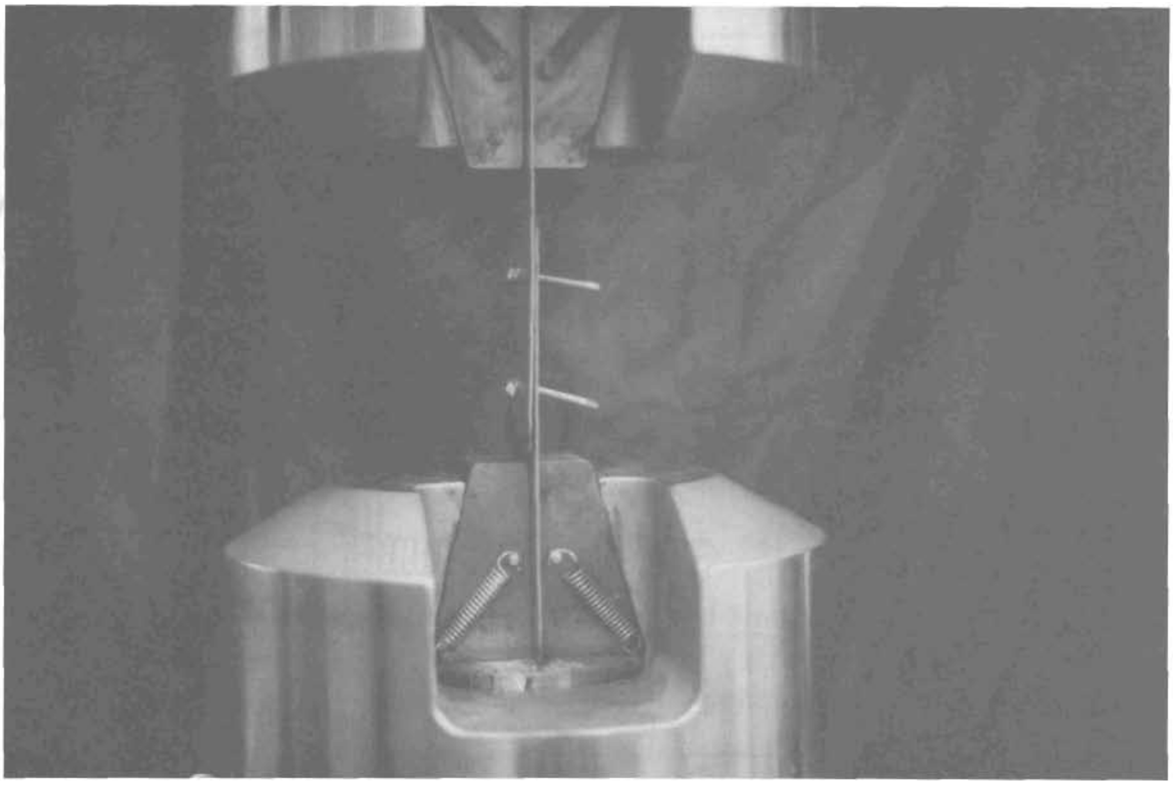

Figure 3.9 Photo of Shear Test Setup Using Two Steel Sheets

Using the test setup as shown in Figure 3.10 gave more consistent failure loads (Table 3.3) than did the fixture of Figure 3.5 (Table 3.2). Tests were performed with both single- and two-screw connections. The per-screw strength was consistent between the single- and two-screw tests, and on the average the two-screw test gave a seven percent lower per screw strength. Due to the conservative nature of the two-screw test, a two-screw test was permitted in the standard test protocol. Standard dimensions for the test specimen were taken from "Test Procedures for use with the 1996 Edition of the Cold-Formed Specification" (AISI, 1996b).

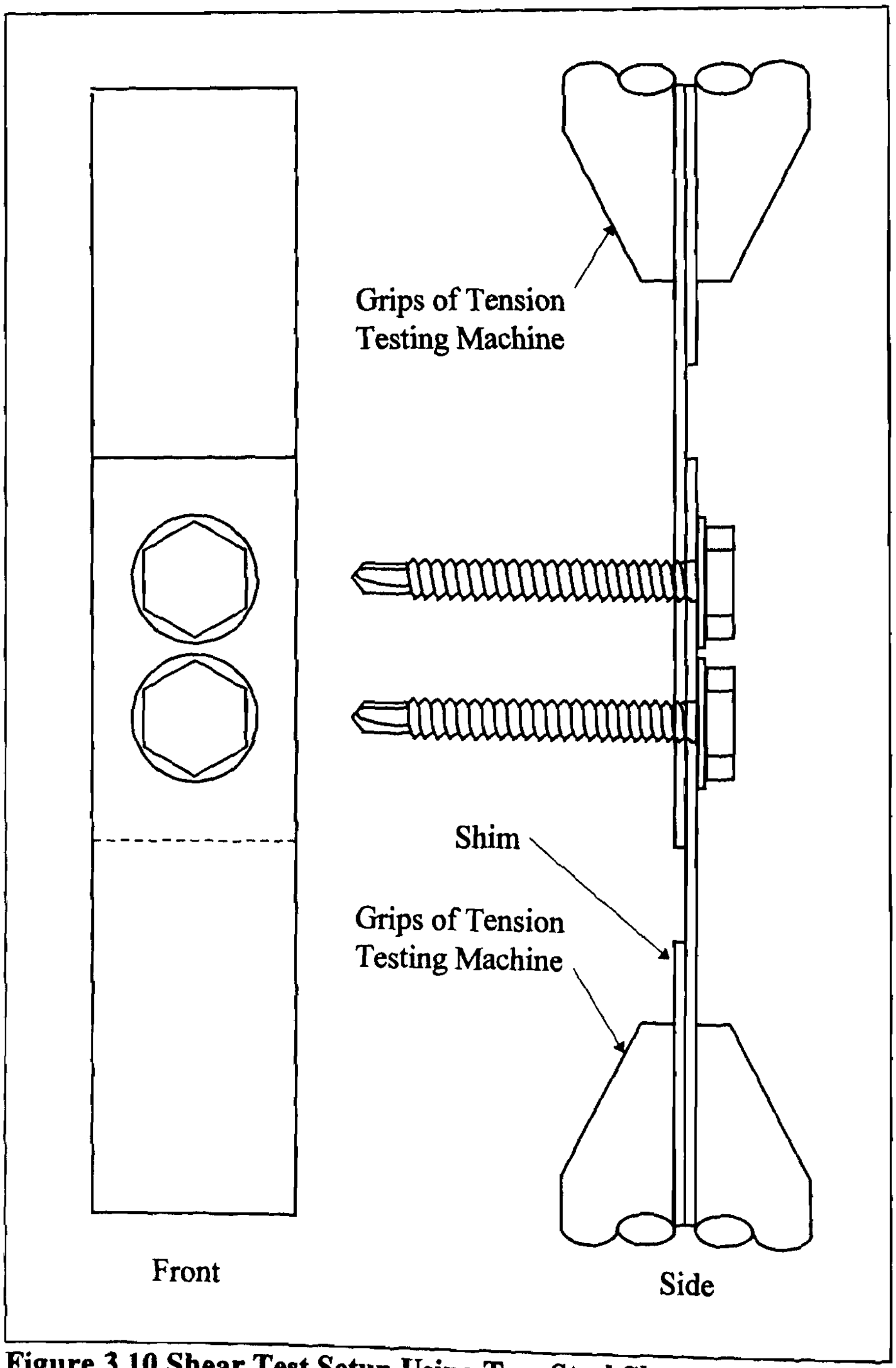

Figure 3.10 Shear Test Setup Using Two Steel Sheets

Table 3.2 Summary of Shear Tests Using Plate Fixture

Test #	Failure Load (lbs)	Setup **	Control: S = Stroke L = Load	Rate: Stroke (in/min) Load (lbs/min)
s1	2080	1	S	0.036
s2	2210 & 2490*	2	S	0.036
s3	1020	1	L	9400
s4	1460	1	L	330
s5	1000	1	L	330
s6	2100	2	L	330
s7	1860	3	L	330
s8	4120	4	L	330
s9	3680	4	S	0.018
s10	2670	5	S	0.18
s11	1980	5	S	0.18

* Two distinct peak loads attained - load sharing was minimal.
** See Figure 3.8 for definition of setup.
Note: The above is for round head screws with square drive.

Table 3.3 Summary of Shear Tests Using Two Steel Sheets

Test #	Failure Load (lbs)	# of Screws	Strength per screw (lbs)	Rate: Stroke (in/min)
s12	2973	2	1487	0.1
s13	3100	2	1550	0.1
s14	1534	1	1534	0.1
s15	1756	1	1756	0.1
s16	1590	1	1590	0.1

Note: #10-16x1-1/2" Traxx hex head screws
Sheet steel was 3.25 inch x 7.63 inch x 0.072 inch
Fy = 66 ksi Fu = 71 ksi
Screw spacing = 2 inch
Edge distance in the line of force = 1 inch

3.4 COMBINED SHEAR AND TENSION

The combined shear and tension test study consisted of an investigation of two different test methods. The first method used the same test fixture that was used for the tension test. The assembly was inserted into the tension testing machine at an angle (Figure 3.11). Representative test values are shown in Table 3.4. Variation of failure loads, and the limited number of tests conducted, suggest that further study of this method may be warranted.

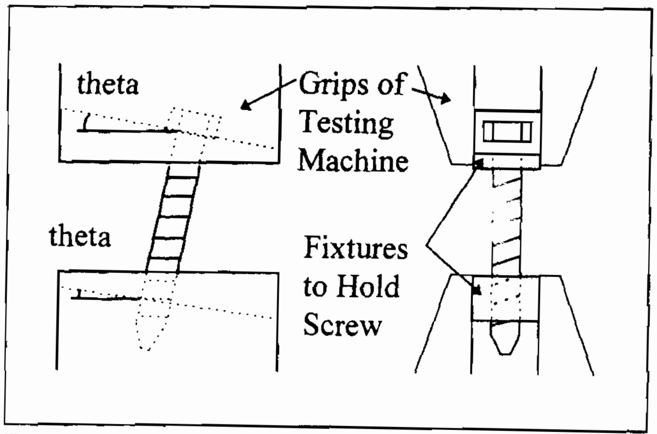

Figure 3.11 Combined Shear and Tension Test Setup

Table 3.4 Combined Shear and Tension Test

Test #	Failure Load (lbs)	Angle from Vertical (degrees)	Rate: Stroke (in/min)
st1	3599	8	0.1
st2	3953	8	0.1
st3	3690	18	0.1
st4	2770	18	0.1

Note: #10-16x1-1/2" Traxx hex head screws.

The second test method was taken from Luttrell (1996). The test setup is given by Figures 3.12, 3.13, and 3.14.

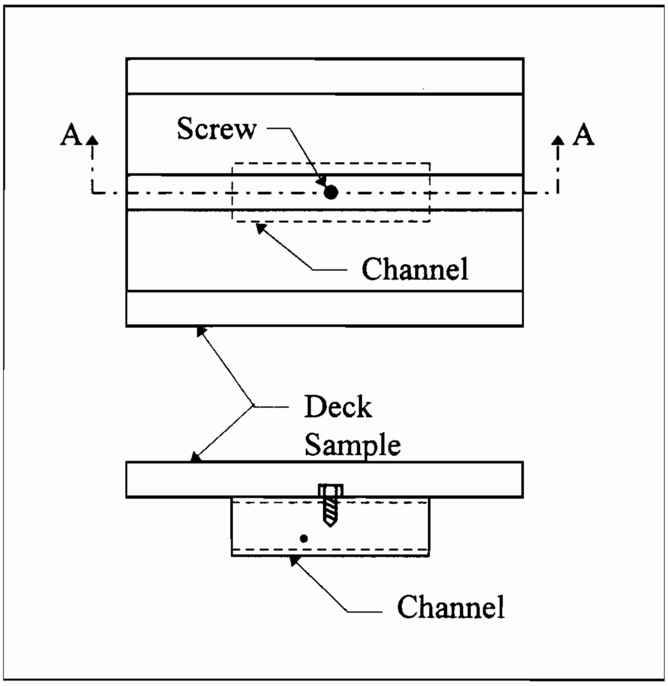

Figure 3.12 Combined Shear and Tension - Deck Assembly

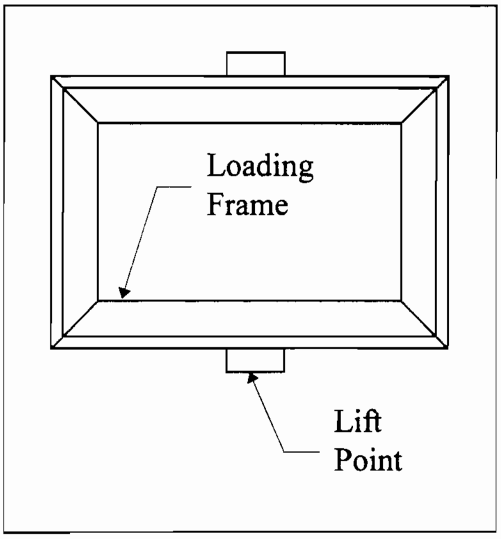

Figure 3.13 Combined Shear and Tension - Loading Frame

As shown by Figure 3.12, a steel deck section was attached to a channel section using the screw that was to be tested in combined shear and tension. Figure 3.13 shows the loading frame, which was sized to support the steel deck section. Figure 3.14 shows

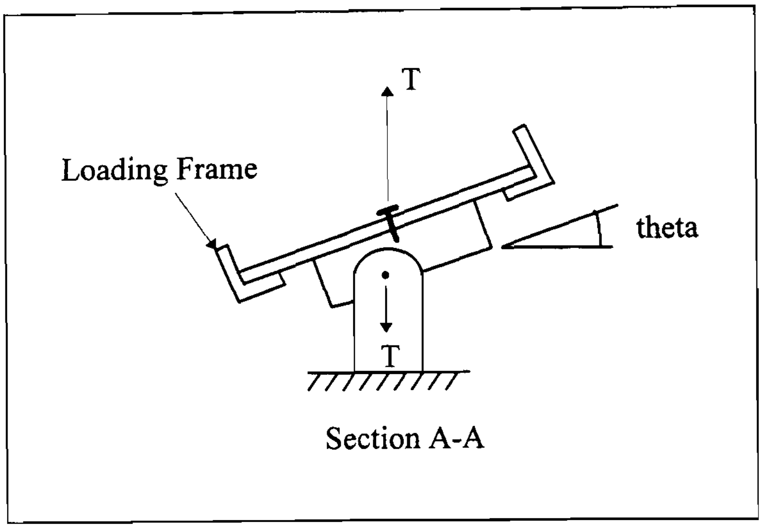

Figure 3.14 Combined Shear and Tension - Test Setup

the final assembly. The steel deck was placed inside of the loading frame, and the channel was anchored by means of a bolt through a hole in the side of the channel. A load was applied through the lift points, thus putting the screw into combined shear and tension. This test models the type of loading that is most likely to occur in an actual structure. The deck section must be thick enough to prevent pull-out and pull-over failures. The bolt hole in the channel must line up with the line of force applied to the screw. The "theta" angle (Figure 3.14) determined the components of "T", the tension force supplied by the testing machine, that were tension and shear on the screw. The angle may be varied to vary the proportions of tension and shear on the screw.

No tests were performed with this setup during this study, however Luttrell provided test data, verifying the test procedure.

3.5 TORQUE - TENSION CORRELATION

For screws too short to test in tension using the fixtures of Section 3.2, a means was needed by which to determine the tensile strength. Two concepts were pursued. Each concept relates tension strength of the screw to some other more easily measurable property of the screw. The two concepts considered were the use of screw hardness and use of the screw torsion strength.

Relating screw hardness to tensile strength is a technique that may be currently used for determining the bolt tensile strength (ASTM, 1995). The screw is case hardened to make the outside of the screw durable during the drilling and tapping. This case hardening creates a variation in hardness through the cross-section that is difficult to quantify. Several hardness measurements would be necessary across the cross-section of the screw shank. The shank of a screw is small in diameter, and therefore hardness testing would require the use of micro-hardness testing equipment, which is not readily available. To quantify the hardness requires making a metallurgical mount of the screw cross-section. After metallographically polishing the mount, a scanning electron microscope, or an optical microscope, would be used to measure the case depth. Then using the rule of mixtures, that is proportioning hardnesses weighted by the area to which they apply, an average hardness value could be calculated for the screw cross-section. This hardness value could then be correlated to the tension strength of the screw, using ASTM A 370-97a (ASTM, 1997) or by multiplying the Brinell hardness number by 500.

The use of hardness is impractical, so a more efficient method was sought. A limited study was performed to correlate the tensile strength of the screw to the torque required to break the screw in a torsion test. The torsion test consisted of placing the screw in a vice, which clamped the screw threads sufficiently to prevent rotation of the screw. Care was taken to prevent crushing of the screw threads when clamped in the vice. A torque wrench was used to twist the head of the screw, which projected above the vice, until the screw failed in torsion. The torsion at failure, which was the maximum torsion that the screw withstood, was called the torsion strength.

Three screw types were investigated, and the results of the 17 tests are listed in Appendix C. The average of the test results are listed in Table 3.5, along with the torsion/tension ratio.

Table 3.5 Tension vs. Torsion Correlation

Screw Type	Mean Tensile Strength (lbs)	Tensile Strength COV	Mean Torsion Strength (in-lbs)	Torsion Strength COV	Torsion/ Tensile Ratio ((in-lb)/lb)
#12-12x3"	2997	0.01	96.25	0.03	0.032
#10-16x1-1/2"	2886	0.10	86.75	0.06	0.030
#12-14x3"	3852	0.06	136.5	0.04	0.035

During the torsion tests, the screws tended to break either near the head or where the screw threads were clamped near the top of the vice. The clamping location was varied between near the top and near the bottom of the threaded shank of the screw. The torsion at failure, however, was consistent regardless of the location of clamping. The average torsion/tension ratio ranged from 0.032 to 0.035, with coefficients of variation from 0.01 to 0.10. A ratio of 0.035 was recommended in the standard test (Appendix A) in order to yield a conservative estimate of the tension strength.

4. RESULTS FOR CONNECTION STRENGTH

4.1 GENERAL

Screw connection strength equations in the current American Iron and Steel Institute's *Cold-Formed Steel Design Manual* (AISI, 1996) are based on a data base of over 3500 tests (Pekoz, 1990). Because the test parameters involved are broad, there is much scatter in the data, and the design equations were conservatively developed.

This study has focused on design parameters typically found in residential construction in the United States. Patterns, spacing, and number of screws were varied to determine their effect on connection strength. Previously, screw patterns and spacing had not been studied extensively. Design equations for establishing the connection strength have been developed.

The connection strength study involved testing of 200 single lap connections of normal ductility steel sheets. Three sheet thicknesses (Appendix E, Table E.1) were considered. Three self drilling screw sizes, #8, #10, and #12 were studied. Unique to this research was the study of the influence of the number of screws, geometric pattern formed by the screws, and the spacing of the screws. The number of screws in a connection varied from 1 to 12 and formed 27 different geometric patterns. Two different screw spacings were investigated, 2d and 3d, d being the outer diameter of the screw threads. The effect of stripped screws on connection strength was also studied. Appendices D through M detail the sheet and screw dimensions, sheet material properties, test data and patterns, and graphs.

Bearing failure was the failure mode that was the focus of this study. Currently the American Iron and Steel Institute (AISI, 1996) specifies a minimum of 3d spacing, d being the outer diameter of the screw threads. In this study, 2d spacing was a lower bound because screw heads interfered with each other at spacings less than this. Edge distances as specified by the *Cold-Formed Steel Design Manual* (AISI, 1996) were maintained (1.5d transversely and 3d longitudinally).

4.2 TEST SPECIMEN

Figures 4.1 and 4.2 show the general test setup. Sheets were always 12 inch long, and a three inch length was clamped inside the jaws of the tension testing machine. Two sheet widths were used - 1-7/8 inch and 2-7/8 inch.

Three different sizes of self-drilling screws were used, and each screw size determined the minimum spacings required (for screw dimensions see Appendix D, Tables D.5 through D.8). For longitudinal and transverse spacing of screws, Section E3.1 of *Specification for the Design of Cold-Formed Steel Structural Members* (AISI, 1996) was referenced. According to the specification (AISI, 1996), screw spacing and longitudinal edge distance parallel to the direction of force (Figure 4.1), must not exceed 3d, where d is the outside diameter of the screw. Transverse edge distance must not be less than 1.5d according to the AISI specification (AISI, 1996).

The screw pattern was centered transversely on the sheet, with the first row of screws occurring at the minimum longitudinal edge distance from the edge of the sheet. The minimum transverse edge distances were met or exceeded. Screw spacing was measured transversely and longitudinally, not diagonally. Diagonal spacing met or exceeded the minimum screw spacing.

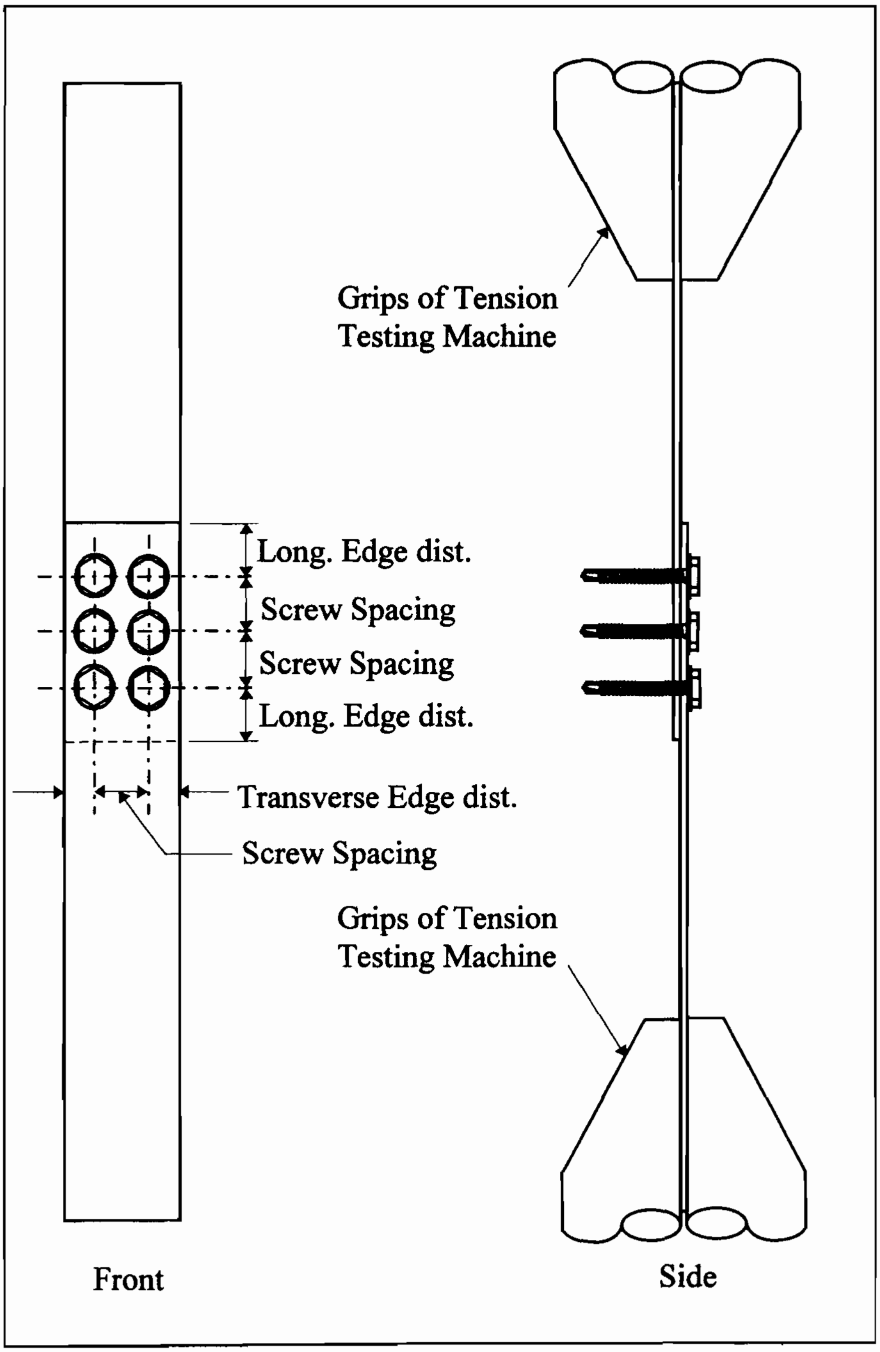

Figure 4.1 General Test Setup for Connection Tests

To fabricate a test specimen, a 24 inch long sheet was cut in half to form two 12 inch long sheets that would be screwed together. The sheet was cut in half with a chop saw. The cutting introduced heat into the test sheet, therefore the cut ends of the 12 inch sheets, when the connection was tested, were placed in the grips of the tension testing machine, rather than being used in the area of the connection. Thus, the cutting procedure did not affect the connection strength.

Figure 4.2 Connection Test Setup

One 12 inch sheet was marked with the screw pattern. The two 12 inch sheets were lined up on a flat surface, clamped and placed in a vice to prevent gaps between the sheets. A screw gun with variable torque control was used to insert the screws. The variable torque control was used to prevent screw stripping. The screw drilled its own hole, after which the screw threads drove the screw into the sheets until the head of the screw bore snugly against the sheet.

4.3 TEST PROCEDURE

The connected sheets were placed into a Materials Test System 880 (MTS) testing machine and loaded until failure occurred. A three inch length at each end of the sheet was clamped by the machine's jaws. The machine then automatically applied a stroke rate of 0.1 inch per minute, and recorded the applied load. The test was continued until a failure load was reached. Connection strength was defined as the maximum load at failure.

4.4 GENERAL RESULTS

When fracture occurred, it almost always occurred in the sheet that had the screw threads exposed, rather than the sheet against the screw head. Maybe this occurred because when the screws tilted, which occurred early in the test, part of the head would bear against the sheet, spreading the load over a wider area. Therefore, the sheet that had only the screw threads bearing against it had a smaller bearing area. Figure 4.3 shows examples of connection behavior that were encountered. From left to right in this figure, the behaviors are screw shear, bearing failure of the sheet, fracture of the sheet between the screws, and cupping of the material around the connection.

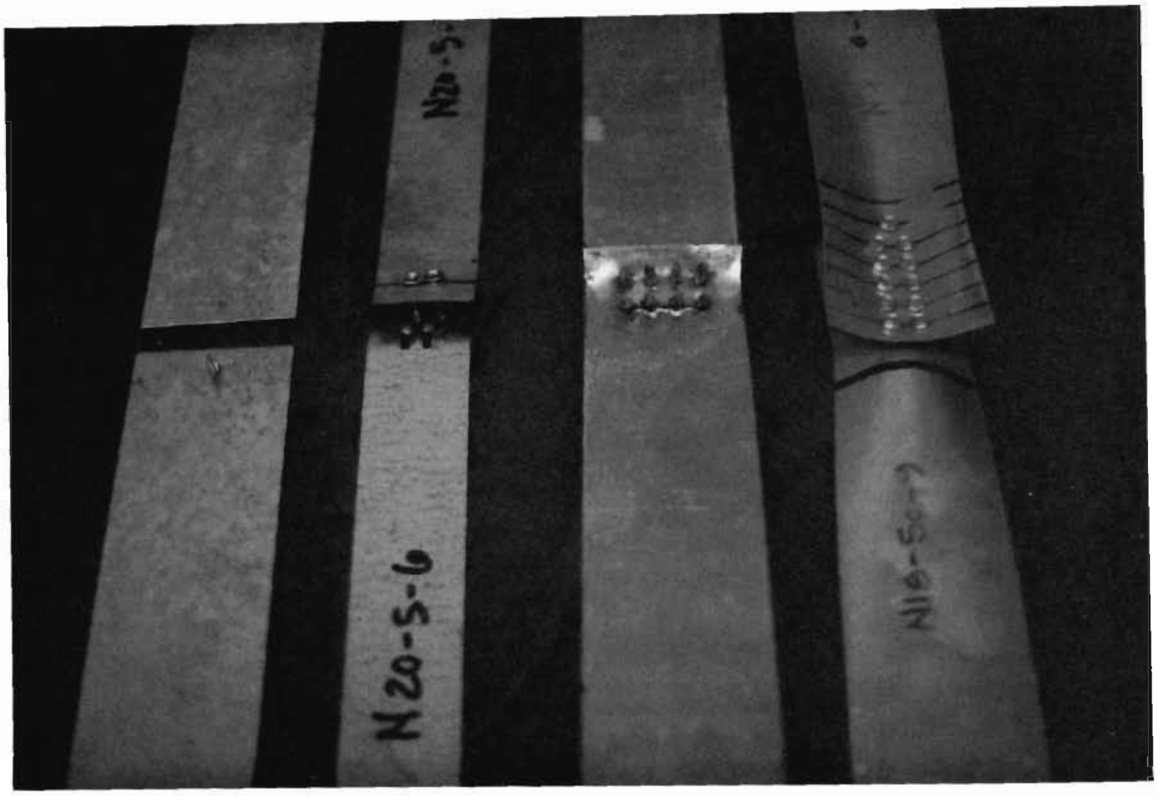

Figure 4.3 Behavior of Connections

When there were several rows of screws, fracture occurred through the row closest to the jaws of the testing machine.

Bearing failures and tilting with bearing were the desired failure mode. Typically, for larger number of screws, the sheet would fracture. For the 16 gage sheet, when the number of screws was small, one or two, failure was by bearing and then shear of the screws. If fracture if the sheet was experienced in the two inch wide sheet, then a three inch wide sheet was used to allow for testing of greater number of screws. Some tests of connections with two inch and three inch sheet widths were performed in which the screw pattern was identical to demonstrate that the connection strength was independent of the sheet width.

Strength per screw was calculated and is summarized in Appendix F. A connection with one screw had a higher strength than the strength per screw for a multiple screw connection with the same screw and steel sheet size. To quantify this effect, a "Group Effect" was created that normalized connection strength with respect to single screw strength. This "Group Effect" is the strength per screw divided by the connection strength for a single screw connection. If all screws in a connection acted and contributed equally, the "Group Effect" would be 1.0. Current design equations are based on a single screw connection, and the strength of multiple screw connections is assumed to be a direct multiple of the single screw connection strength. This assumption would give a "Group Effect" of 1.0, that is, any number of screws in a connection would have the same strength per screw as a similar single-screw connection. The "Group Effect" calculated from the data shows that this assumption is not valid.

4.5 EFFECT OF PATTERN

A total of 27 different geometric screw patterns were tested. The screw patterns and test results may be seen in Appendix F. Table 4.1 shows data for some four screw patterns, and is arranged in order of strength.. Figure 4.4 shows the patterns. As indicated by the "Group Effect" in Table 4.1, varying the screw pattern did not significantly vary the strength of the connection. These "Group Effect" values were within +/- 7% of the average. A general trend can be seen: with the exception of pattern 4E, the more rows of screws the connection had, the higher strength the connection had. A row is defined as a line of screws transverse to the direction of loading. This generality makes sense conceptually because more rows of screws gives more rotational stability to the

Table 4.1 Typical Results for Four Screw Patterns

Pattern	Connection Strength (lbs)	Connection Strength per screw (lbs)	Group Effect	% from Mean
4C	1492	373	0.71	-4.1
4A	1506	377	0.72	-3.2
4A	1524	381	0.72	-2.0
4B	1559	390	0.74	0.2
4B	1563	391	0.74	0.5
4E	1583	396	0.75	1.8
4D	1663	416	0.79	6.9

Note: N20 Sheets, #8 Screw, 3d Spacing

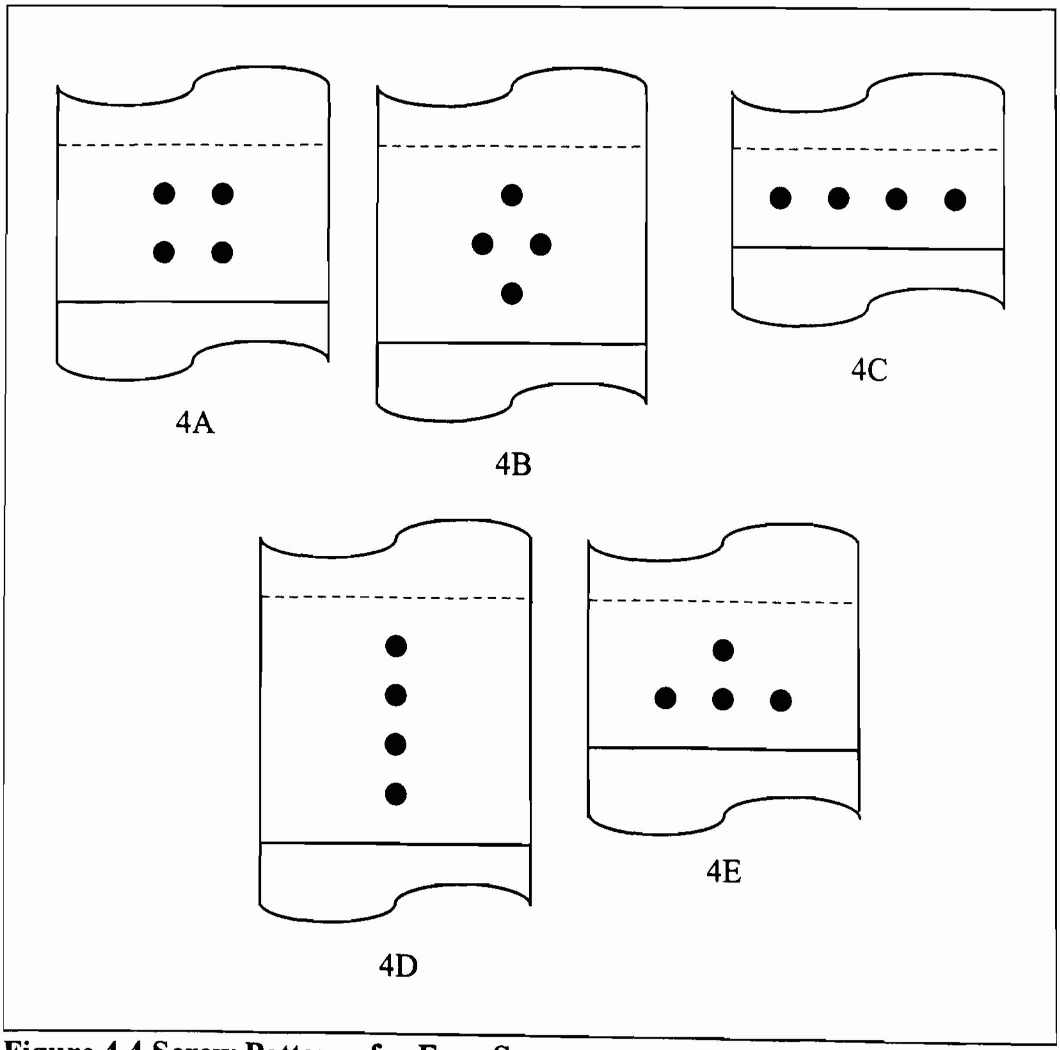

Figure 4.4 Screw Patterns for Four Screws

connection. That is, when the connection is loaded, loading is eccentric because the sheets lap each other. This eccentricity causes the connection to rotate. More rows of screws cause the connection to be more stable against rotation. Less rotation can translate into more strength. When the connection rotates, the screws tilt, and instead of being in shear, the screws are put into tension and shear. This causes the screws to tend to pull out of the steel sheets rather than bear on them, which gives less strength to the connection. Figure 4.5 gives shows the amount of connection rotation that was common in this study.

Figure 4.5 Common Connection Rotation

The "Group Effect" is calculated by dividing a connection's "Connection Strength per screw" by the average of the connection strength values for a single-screw connection that has the same sheet thickness and screw size. To illustrate this, the first value in Table 4.1 will now be calculated. From Table F.3 in Appendix F, the connection strength values for N20 sheets, #8 screw, 3d spacing, and pattern 1A are 519 and 534 lbs. The average of these is 523.5 lbs. Dividing the "Connection Strength per screw" for pattern 4C in Table 4.1 above, by the average just calculated, one gets 373/523.5, or 0.71, which is the "Group Effect" given in Table 4.1.

The trend of more strength for more rows of screws was seen repeatedly, for example for the two-screw patterns 2A and 2B (Tables 4.2, 4.3, and 4.4). Figure 4.6 shows the patterns. Pattern 2A generally had less strength than pattern 2B. When connections had the 2A pattern the screws tended to pull out of the sheet, if the test was allowed to progress that far. Generally tests were terminated when a definite peak was reached in loading. The 2B pattern offered more resistance to rotation, and therefore developed better structural performance.

Table 4.2 Effect of Number of Rows on Connection Strength #1

Pattern	Strength (lbs)	Strength per screw (lbs)	Group Effect
2A	1146	573	0.83
2A	1197	599	0.87
2B	1188	594	0.86
2B	1281	641	0.93

Note: N18 Sheets, #8 Screw, 3d Spacing - 2 Screw Patterns

Table 4.3 Effect of Number of Rows on Connection Strength #2

Pattern	Strength (lbs)	Strength per screw (lbs)	Group Effect
2A	749	375	0.71
2A	789	395	0.75
2B	900	450	0.85
2B	844	422	0.80

Note: N20 Sheets, #8 Screw, 3d Spacing - Two Screw Patterns

Table 4.4 Effect of Number of Rows on Connection Strength #3

Pattern	Strength (lbs)	Strength per screw (lbs)	Group Effect
2A	2652	1326	0.87
2A	2697	1349	0.89
2B	2835	1418	0.93
2B	2812	1406	0.92

Note: N16 Sheets, #10 Screw, 3d Spacing - Two Screw Patterns

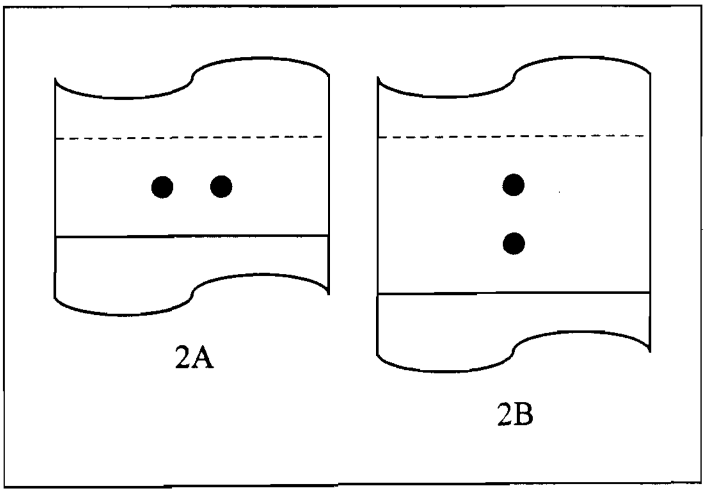

Figure 4.6 Screw Patterns for Two Screws

Another phenomenon that occurred, which was pattern dependent, was the failure of a connection in which the screw pattern did not take up a significant portion of the sheet width. An example of this is shown in Figure 4.7 where pattern 10D does not take up as much of the sheet width as compared to pattern 10A. This is also seen in Figure 4.8 where 12C does not take up as much of the sheet width as compared to 12A. Data comparing these are shown in Tables 4.5 and 4.6. Both of these examples involve fracture, not bearing, failures. Based on the generality developed above, one would expect more strength from the 10D and 12C patterns because there are more rows of screws. But, because the patterns 10D and 12C were narrow with respect to the sheet width, the sheet "cups" under load. That is, the edges of the sheet curled around the screw pattern, so that both lapped sheets curl away from each other (see Figure 4.3, far right specimen). This cupping was caused by the sheet stretching more in the vicinity of the screws, and less at the edges of the sheet.

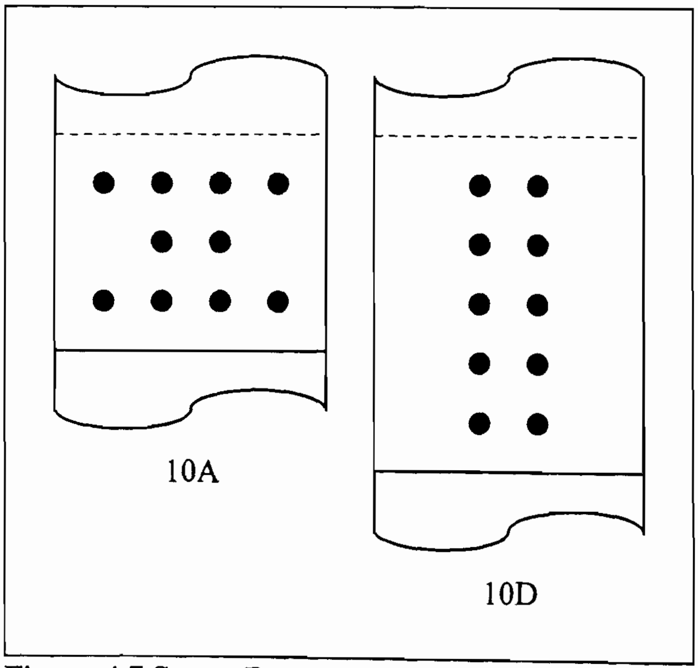

Figure 4.7 Screw Patterns for 10 Screws

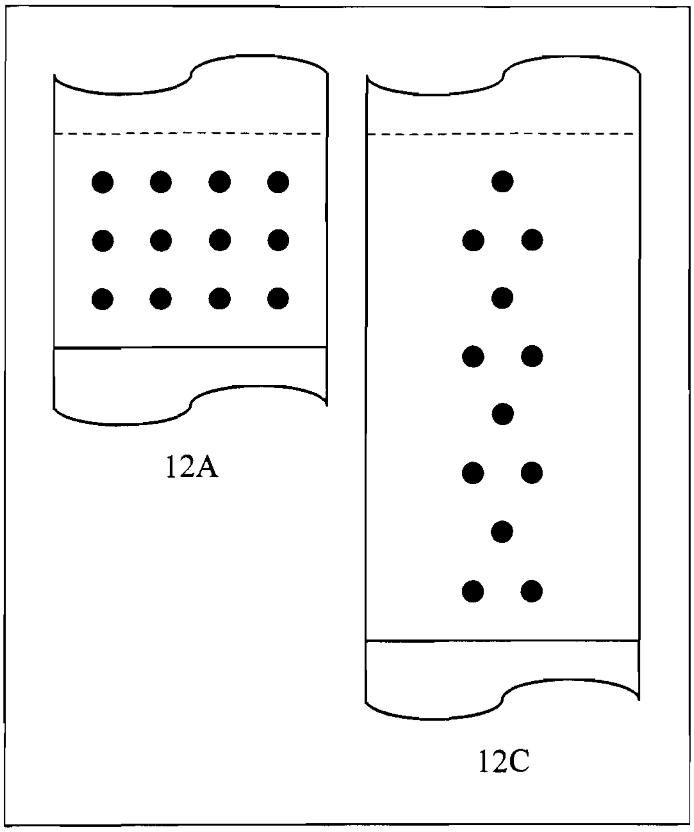

Figure 4.8 Screw Patterns for 12 Screws

Table 4.5 Effect of Cupping - 10A vs. 10D Patterns

Pattern	Strength (lbs)
10A	3329
10D	3067

Note: N20 Sheets, #8 Screw, 3d Spacing

Table 4.6 Effect of Cupping - 12A vs. 12C Patterns

Pattern	Strength (lbs)
12A	3768
12C	2686

Note: N20 Sheets, #12 Screw, 3d Spacing

This same cupping behavior was seen in a bearing failure for an 8-screw connection - see Figure 4.9 and Table 4.7.

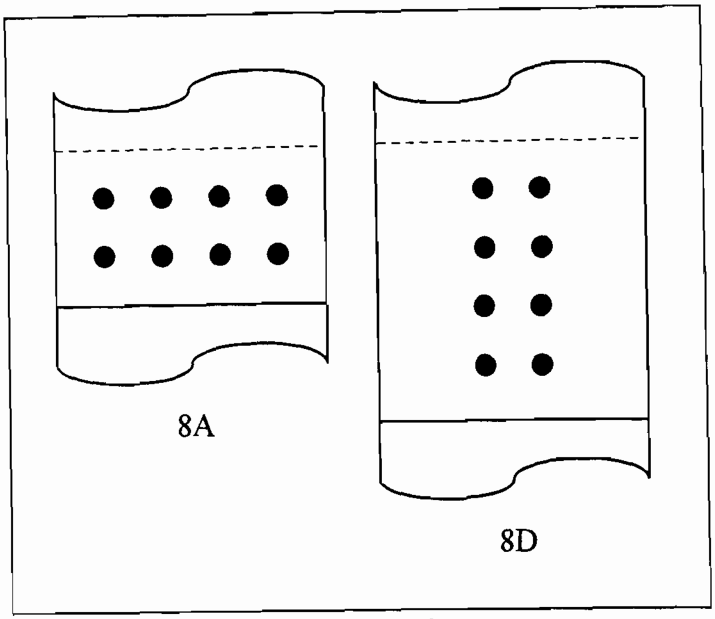

Figure 4.9 Screw Patterns for 8 Screws

Table 4.7 Effect of Cupping - 8A vs. 8D pattern

Pattern	Strength (lbs)
8A	3570
8A	3656
8D	3272

Note: N20 Sheets, #12 Screw, 3d Spacing

A summarizing statement would be that, in a screwed lap connection, more rows of screws lends rotational stability, and therefore more strength to a connection, unless the screw pattern is narrow when compared to the sheet widths that are connected. Overall, when bearing failures occurred however, pattern played little role in the strength of the connection. Strength values were within +/- 10% of the average for a given number of screws in a connection. This +/- 10% can be seen in Appendix F by comparing the "Group Effect" values for a given number of screws in any given chart. This 10% variation is easily achieved in screwed connection tests as a variation in experimental results, and is therefore not considered significant.

4.6 EFFECT OF NUMBER OF SCREWS

Accepted design practice is to assume that if a connection has four screws, it will be four times as strong as a connection with one screw, as long as the sheets being joined do not reach fracture first. For all tests performed, the strength per screw in a connection diminished as the number of screws increased. Figure 4.10 shows a typical relationship between the connection strength and the number of screws.

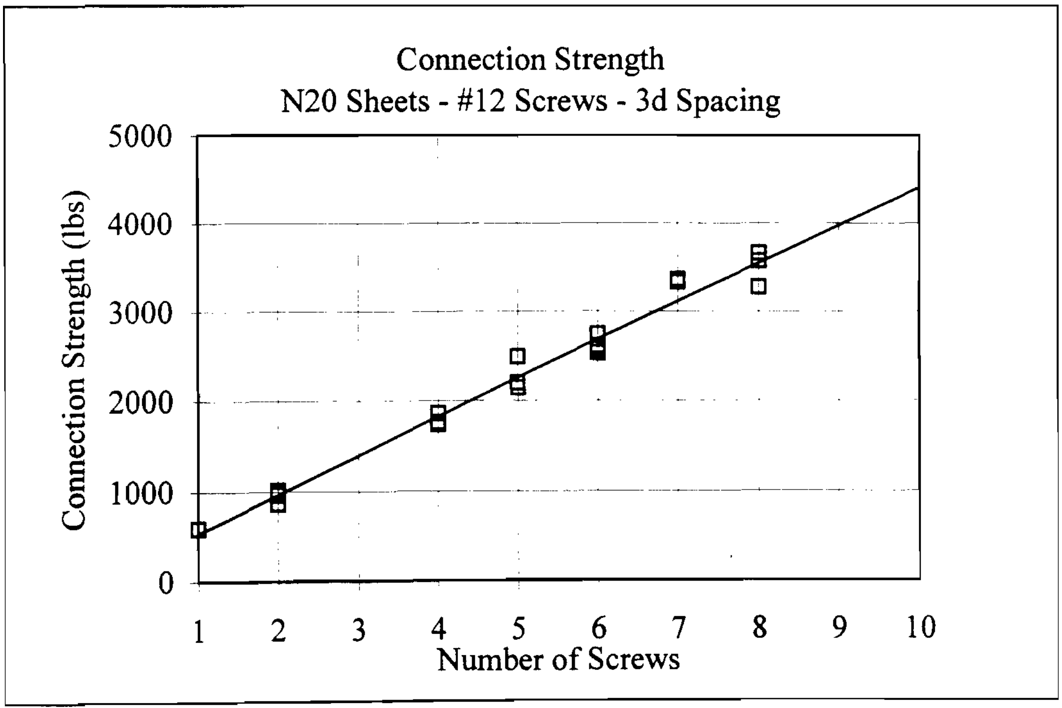

Figure 4.10 Effect of Number of Screws on Connection Strength

As shown by Figure 4.10, the constant slope of the trend line indicates a constant increase in connection strength, but does not give a doubling of connection strength when the number of screws is doubled. A complete set of graphs for all tests may be found in Appendices H, I, and J.

The "Group Effect" is defined as the ratio of the connection strength per screw to the average strength for a single screw connection of the same sheet thickness and screw size. Table 4.8 shows a typical data set, including the "Group Effect" for each connection (data for all tests is given in Appendix F). The "Group Effect" provides an indication of the ability of the fastener group to share the load. Graphically, the relationship between the "Group Effect" and the number of screws is shown by Figure 4.11. This graph shows the diminishing strength per screw as the number of screws increases. A complete set of "Group Effect" graphs for all tests may be found in Appendices K, L, and M.

Table 4.8 Data for N16 Sheets, #10 Screw, 3d Spacing

Pattern	Number of Screws	Strength (lbs)	Strength per screw (lbs)	Group Effect
1A	1	1534	1534	1.01
1A	1	1509	1509	0.99
2A	2	2652	1326	0.87
2A	2	2697	1349	0.89
2B	2	2835	1418	0.93
2B	2	2812	1406	0.92
3A	3	3596	1199	0.79
4A	4	4559	1140	0.75
5B	5	5247	1049	0.69
5C	5	5321	1064	0.70
7A	7	7203	1029	0.68
8B	8	7622	953	0.63
8D	8	7466	933	0.61
9C	9	8094	899	0.59

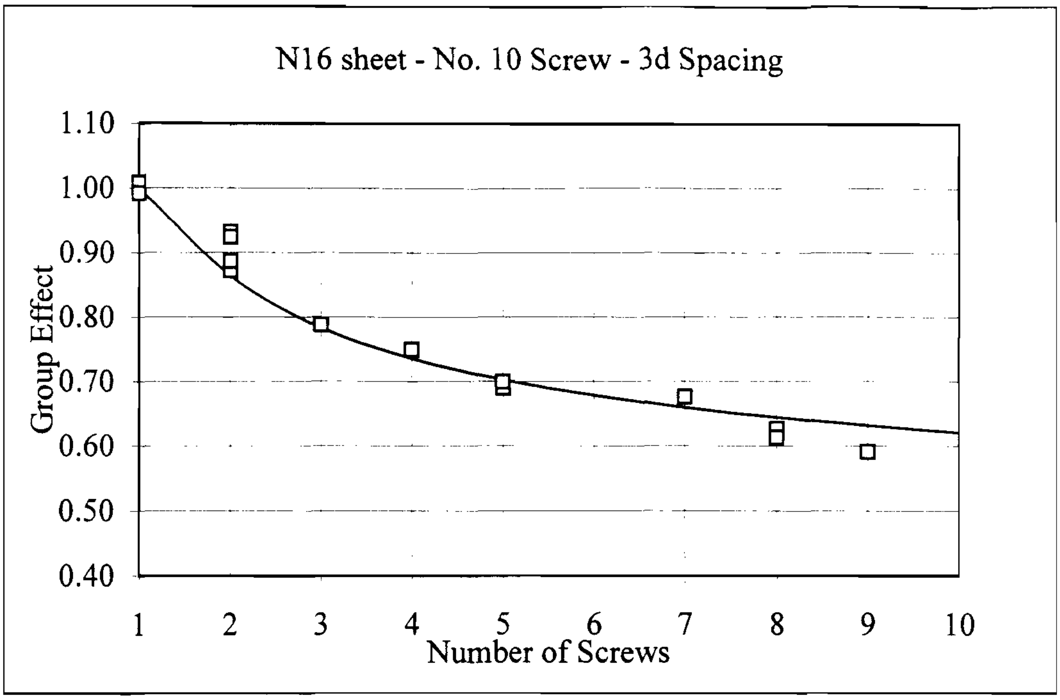

Figure 4.11 Group Effect vs. Number of Screws

4.7 EFFECT OF SCREW SPACING

Screw center-to-center spacing was tested at both 3d and 2d, where d is the outside diameter of the screw threads in the connection. The lower limit of the study was chosen as 2d because at this spacing the heads came in close contact with each other. A sample of the test results are given by Figure 4.12, where the effect of 2d spacing is compared to 3d spacing. A complete set of graphs may be found in Appendix H. It can be seen from the graphs that a closer spacing of screws resulted in a lower connection strength.

4.8 EFFECT OF STRIPPED SCREWS

This study did not focus on stripped screws, but some screw stripping did occur. Stripping occurs as a screw is being driven into the lapped sheets. When the screw head makes contact with the sheet, if the screw continues to spin instead of being drawn snug, it is called a “stripped” screw. Thirteen cases of stripped screws occurred where direct comparison to an identical unstripped connection could be made. The connections with stripped screws were as strong as the identical connection without stripped screws.

Table 4.9 gives examples of stripped screw connections. More examples can be found in Appendix F.

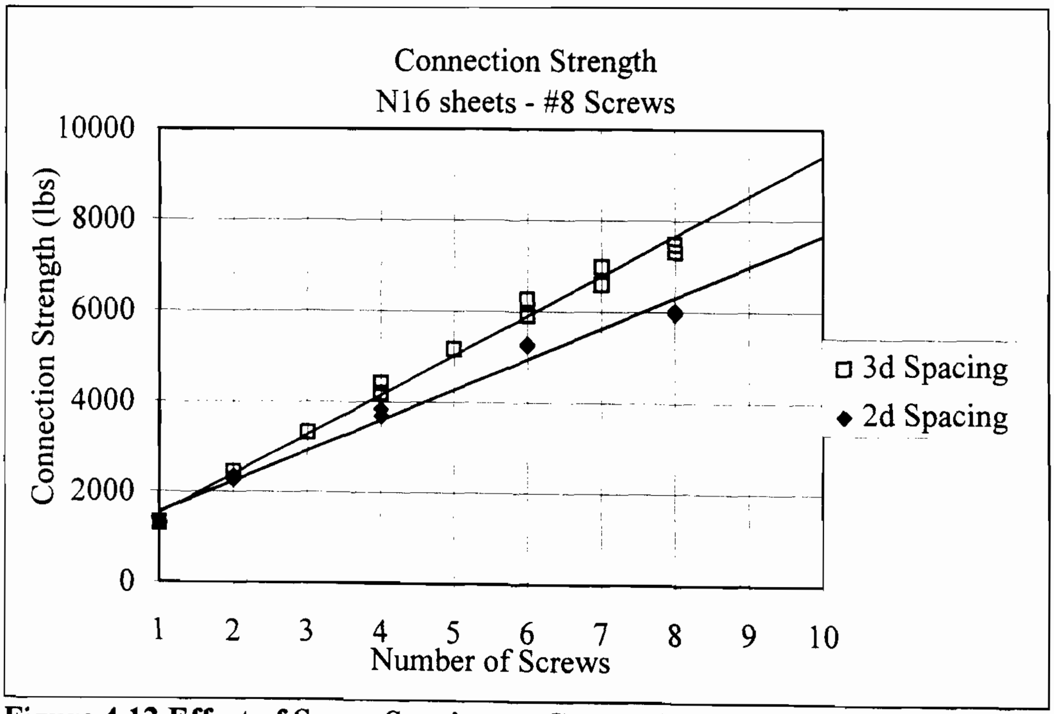

Figure 4.12 Effect of Screw Spacing on Connection Strength

4.9 DESIGN EQUATION

A design equation was sought that would allow calculation of a connection strength based on a single-screw strength equation. The general form of the equation is shown in Equation (4-1).

$$P = nP_1R \tag{4-1}$$

where:

n = number of screws in a connection

P_1 = strength for a single screw connection

R = reduction factor that accounts for the "Group Effect"

Table 4.9 Effect of Stripped Screws

Pattern	Strength (lbs)	Number of Screws in Connection	Number of Stripped Screws
2A	749	2	
2A	789	2	1
2B	844	2	
2B	900	2	1
4A	1524	4	
4A	1506	4	1
8A	2859	8	1
8A	2906	8	2
9A	2896	9	2
9A	2998	9	2

Note: N20 Sheets, #8 Screw, 3d Spacing

The equation for P_1 is based on the research of Minkin (1998) and is given by equation (4-2).

$$P_1 = F_u td\left(2.013\frac{t}{d} + 1.56\right) \tag{4-2}$$

where:

F_u = ultimate tensile strength of steel sheets being joined

t = thickness of sheets being joined

d = nominal screw diameter

The R factor was derived based on all of the "Group Effect" data for test specimens having a center-to-center spacing of 3d or greater. As discussed in Section 4.5, the "Group Effect" was shown to be a function of the number of screws in the connection. Figure 4.13 shows the graph of all 3d data for this connection strength study.

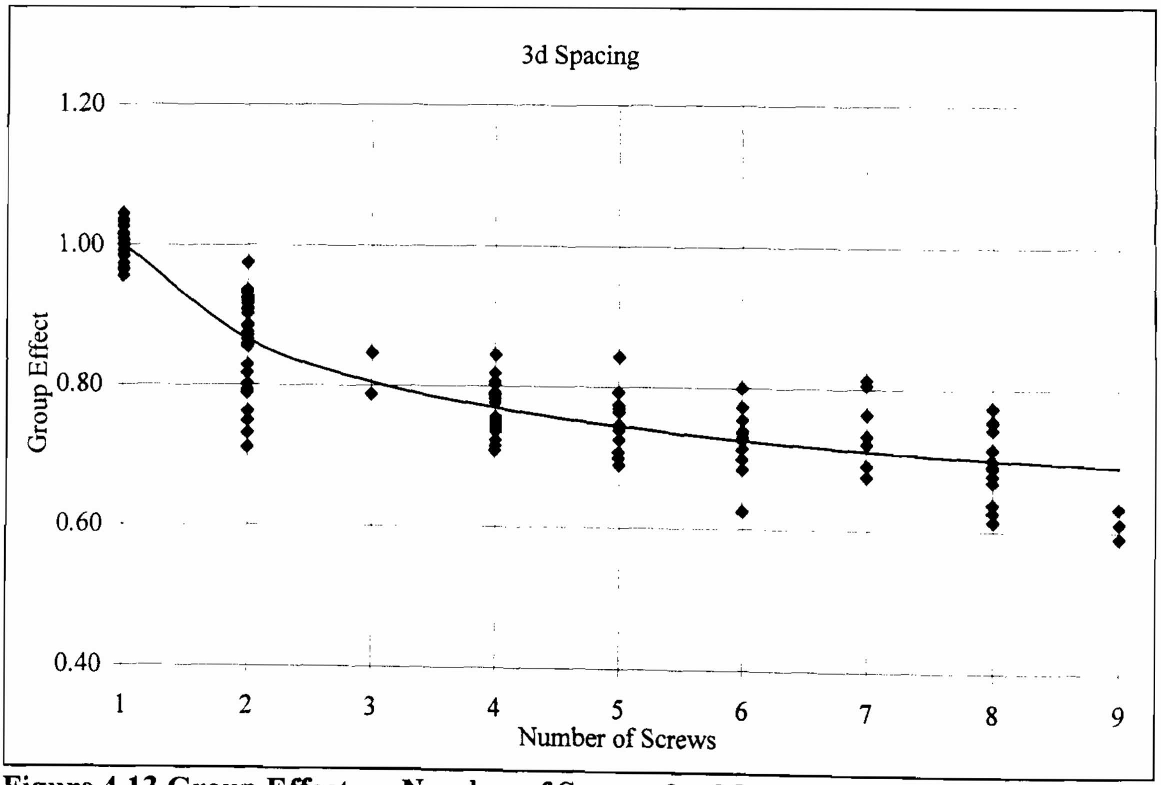

Figure 4.13 Group Effect vs. Number of Screws for 3d Spacing

The best fit curve for Figure 4.13 is given as Equation (4-3).

$$R_{3d} = \left(0.535 + \frac{0.467}{\sqrt{n}}\right) \leq 1.0 \tag{4-3}$$

where:

R_{3d} = reduction factor that accounts for the "Group Effect" for $s \geq 3d$

s = screw center-to-center spacing

d = nominal screw diameter

n = number of screws in connection

A parametric study was conducted to assess the influence of other parameters that may affect the group performance. This study plotted R_{test}/R_{3d} against several parameters including screw thread outer diameter (d), sheet thickness (t), screw spacing (s), longitudinal and transverse edge distances, steel sheet ultimate tensile strength (F_u), ratio of transverse edge distance to sheet width (e/w), ratio of connection area (area bounded by screw pattern) to lapped sheet area (area of sheet overlap), and ratio of transverse edge distance to screw thread outer diameter. The results of the parametric study are given by Figures 4.14 through 4.22. Upon review of these figures, no significant trends can be seen (all trendlines center along the R_{test}/R_{3d} = 1.0).

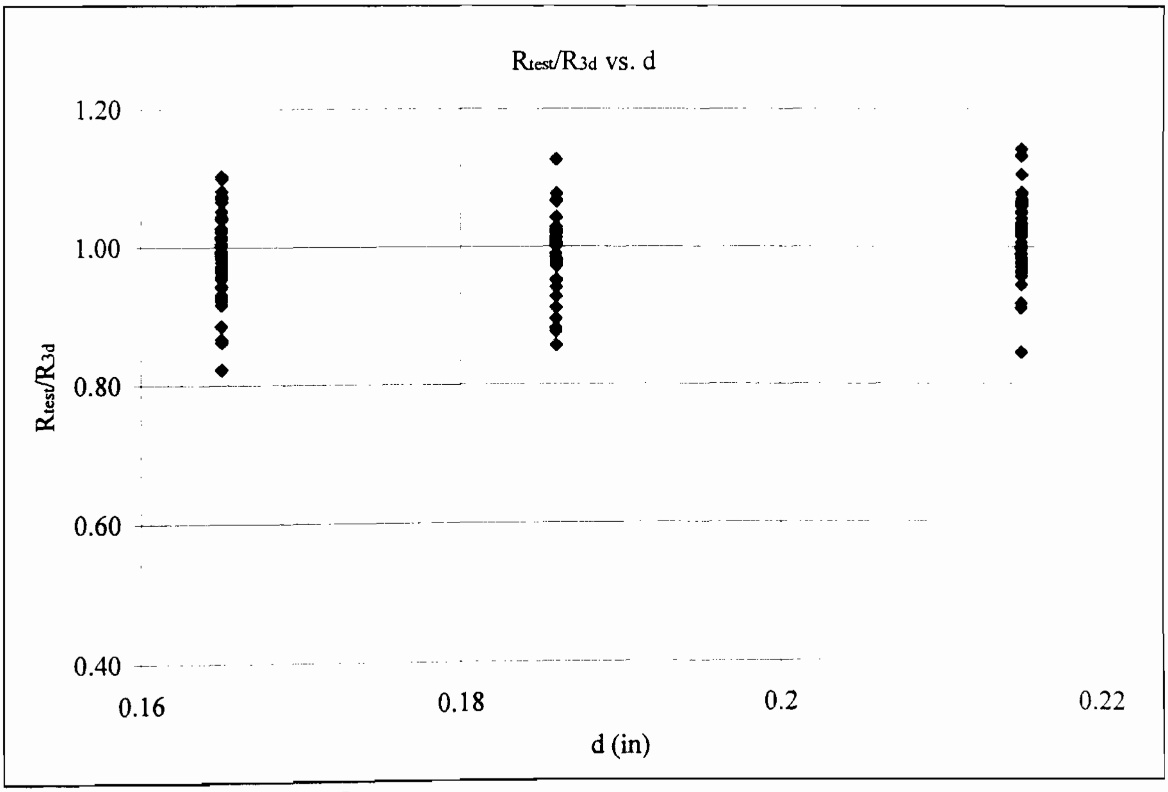

Figure 4.14 R_{test}/R_{3d} vs. d

The R factor was derived based on all of the "Group Effect" data for test specimens having a center-to-center spacing of 3d or greater. As discussed in Section 4.5, the "Group Effect" was shown to be a function of the number of screws in the connection. Figure 4.13 shows the graph of all 3d data for this connection strength study.

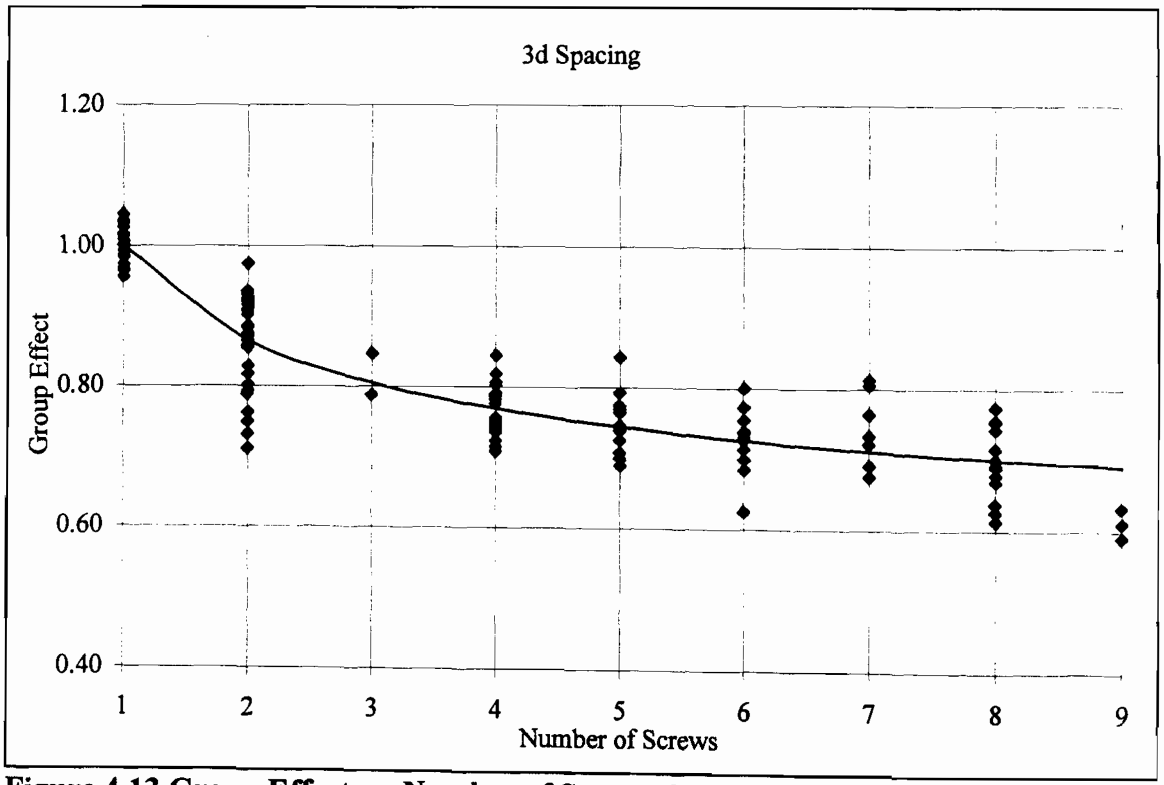

Figure 4.13 Group Effect vs. Number of Screws for 3d Spacing

The best fit curve for Figure 4.13 is given as Equation (4-3).

$$R_{3d} = \left(0.535 + \frac{0.467}{\sqrt{n}}\right) \leq 1.0 \qquad (4\text{-}3)$$

where:

R_{3d} = reduction factor that accounts for the "Group Effect" for $s \geq 3d$

s = screw center-to-center spacing

d = nominal screw diameter

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A parametric study was conducted to assess the influence of other parameters that may affect the group performance. This study plotted R_{test}/R_{3d} against several parameters including screw thread outer diameter (d), sheet thickness (t), screw spacing (s), longitudinal and transverse edge distances, steel sheet ultimate tensile strength (F_u), ratio of transverse edge distance to sheet width (e/w), ratio of connection area (area bounded by screw pattern) to lapped sheet area (area of sheet overlap), and ratio of transverse edge distance to screw thread outer diameter. The results of the parametric study are given by Figures 4.14 through 4.22. Upon review of these figures, no significant trends can be seen (all trendlines center along the R_{test}/R_{3d} = 1.0).

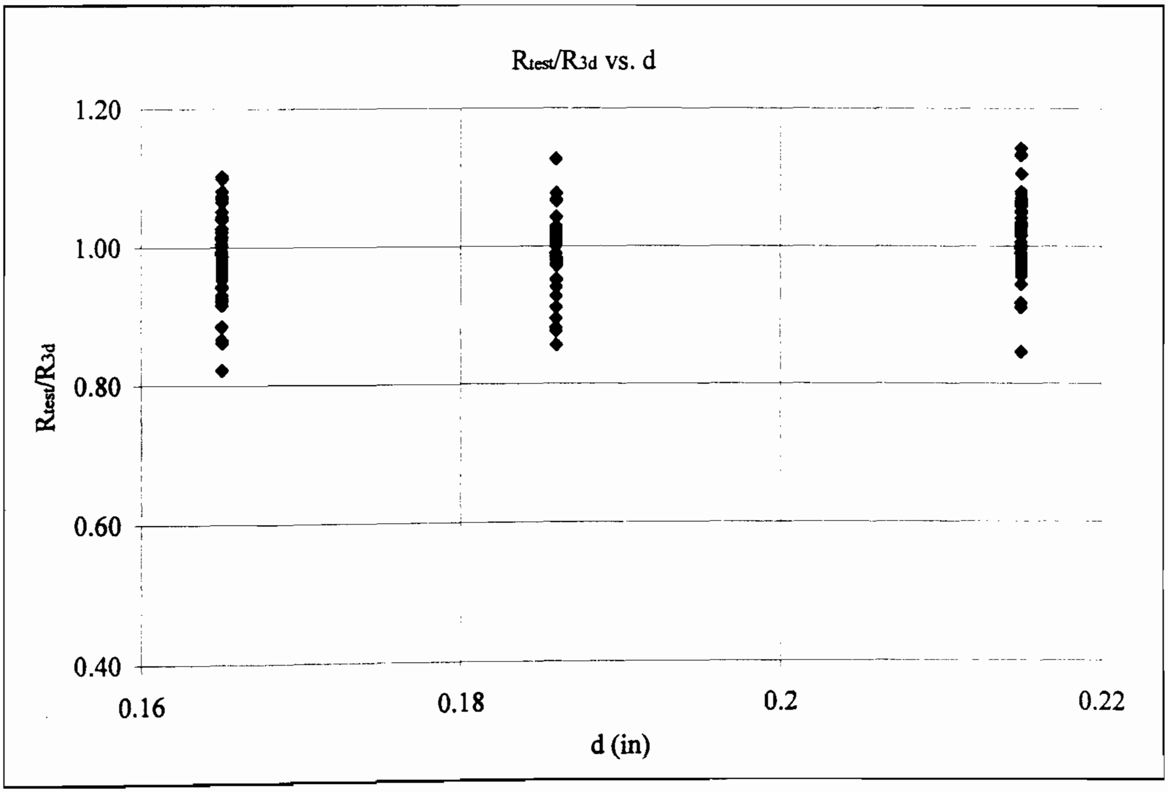


Figure 4.14 R_{test}/R_{3d} vs. d

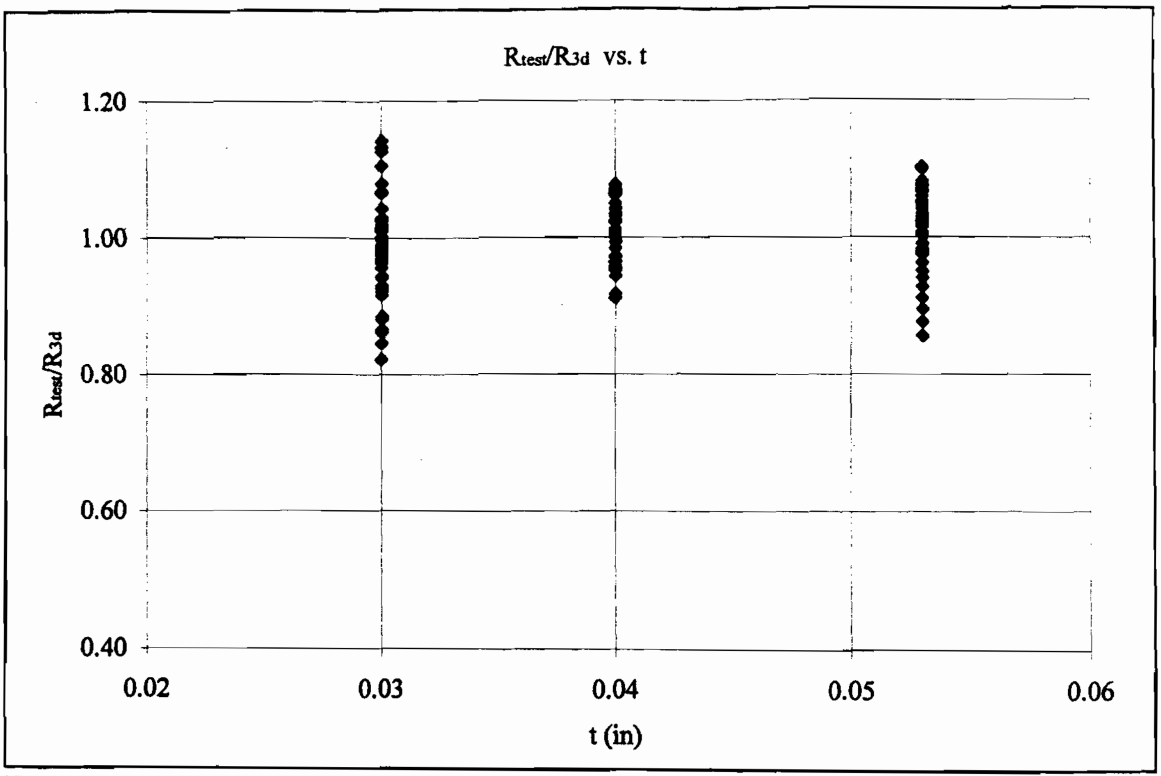


Figure 4.15 R_{test}/R_{3d} vs. t

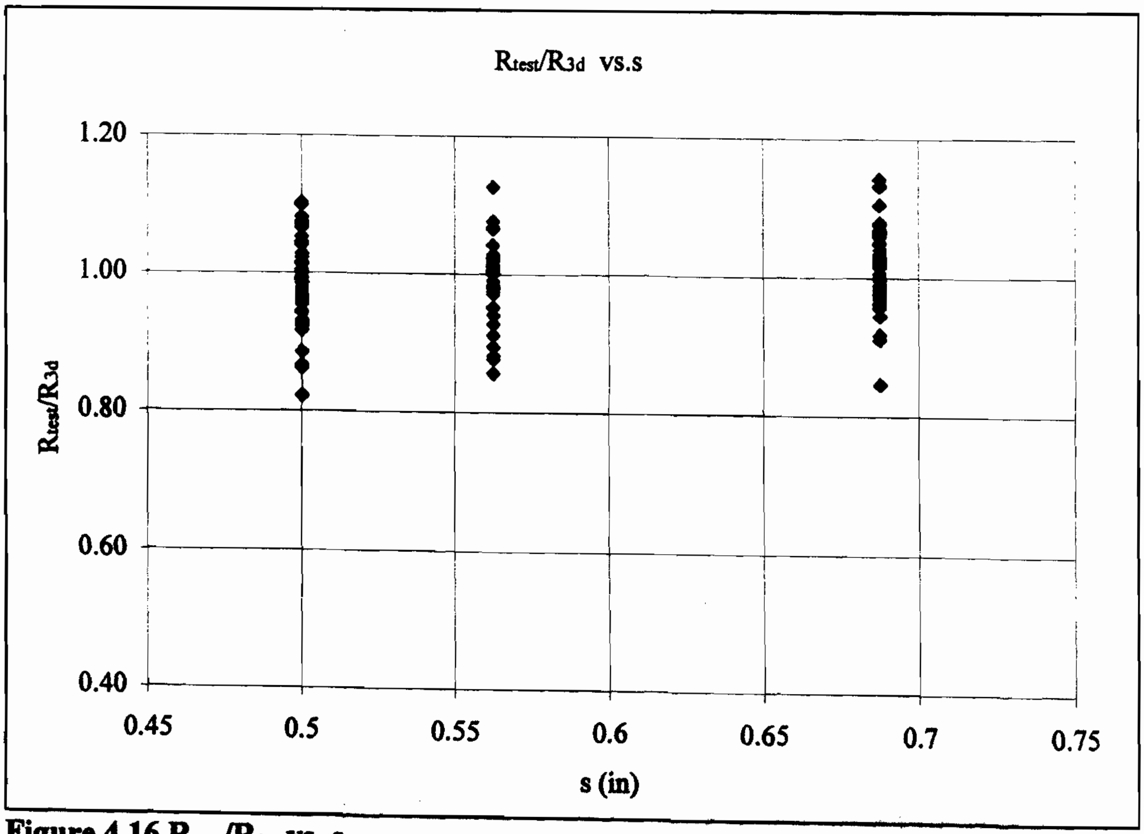


Figure 4.16 R_{test}/R_{3d} vs. s

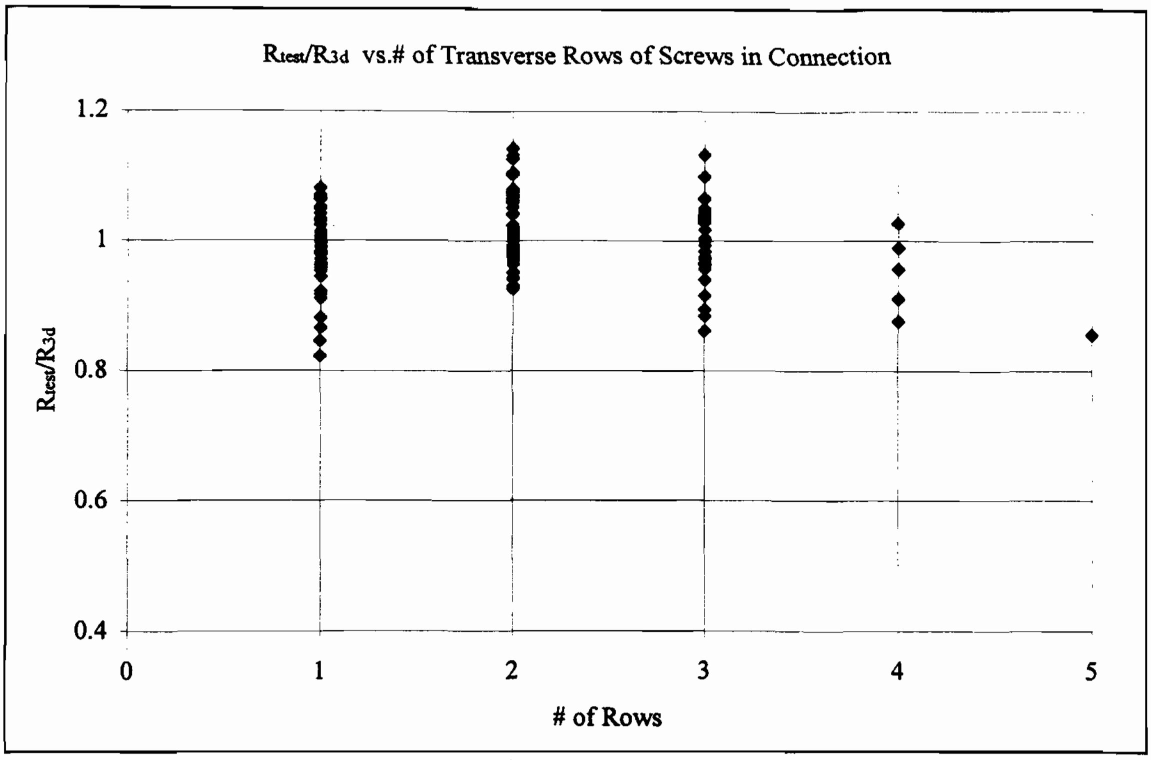


Figure 4.17 R_{test}/R_{3d} vs. Number of Transverse Rows in Connection

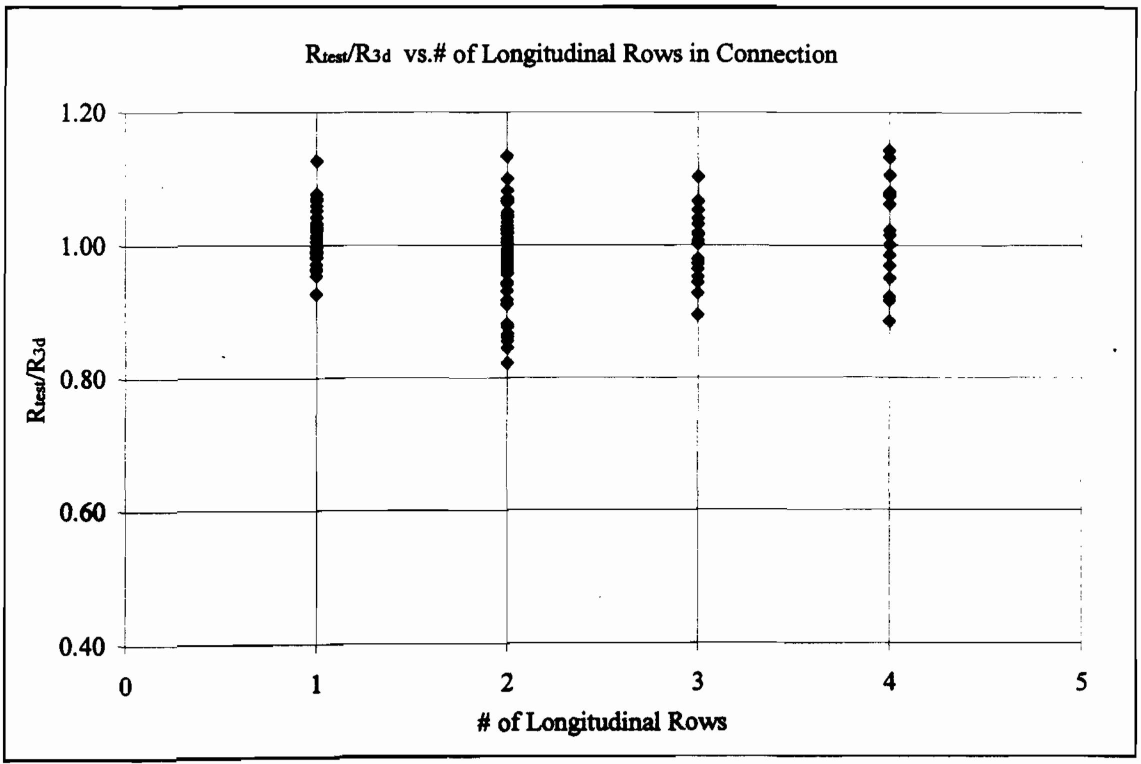


Figure 4.18 R_{test}/R_{3d} vs. Number of Longitudinal Rows in Connection

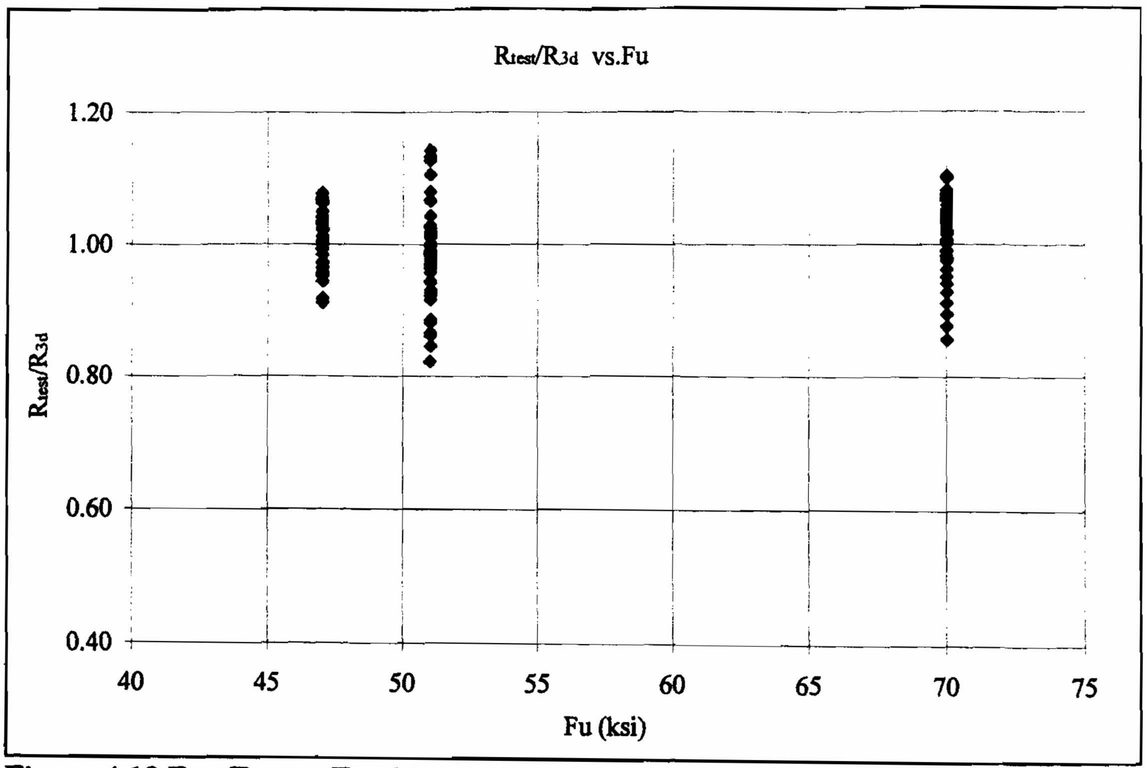


Figure 4.19 R_{test}/R_{3d} vs. F_u of Steel Sheets

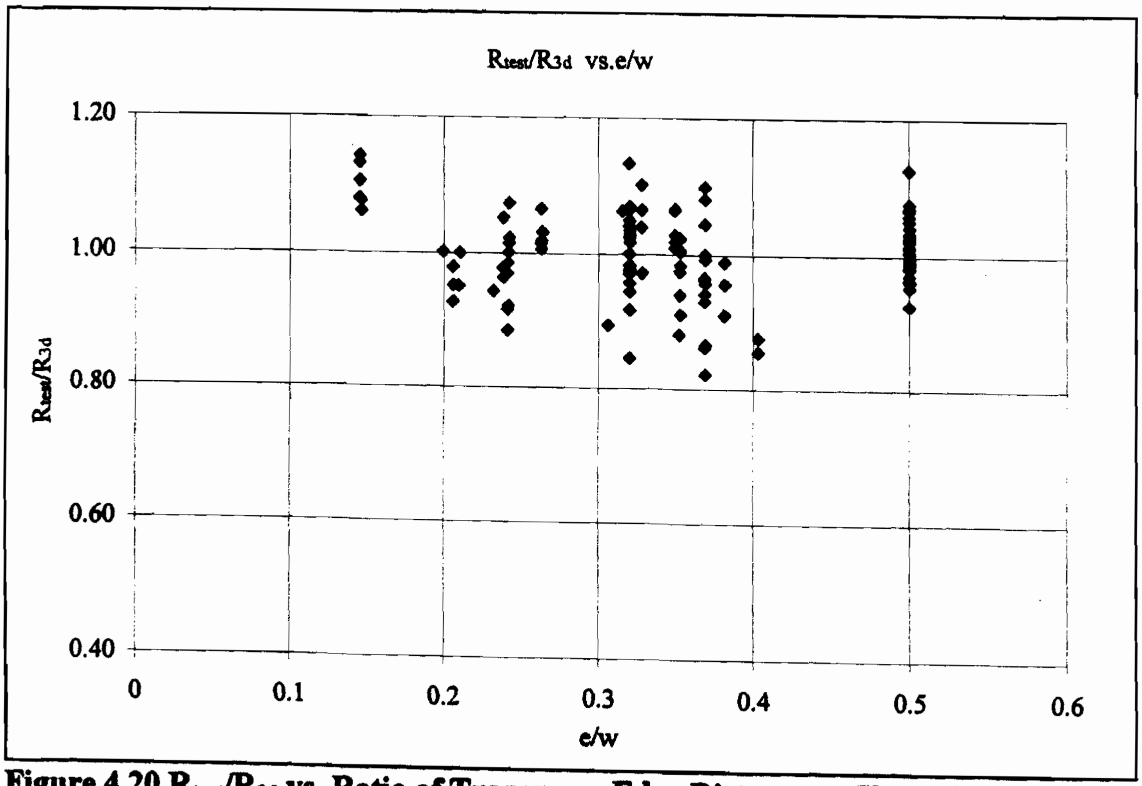


Figure 4.20 R_{test}/R_{3d} vs. Ratio of Transverse Edge Distance to Sheet Width

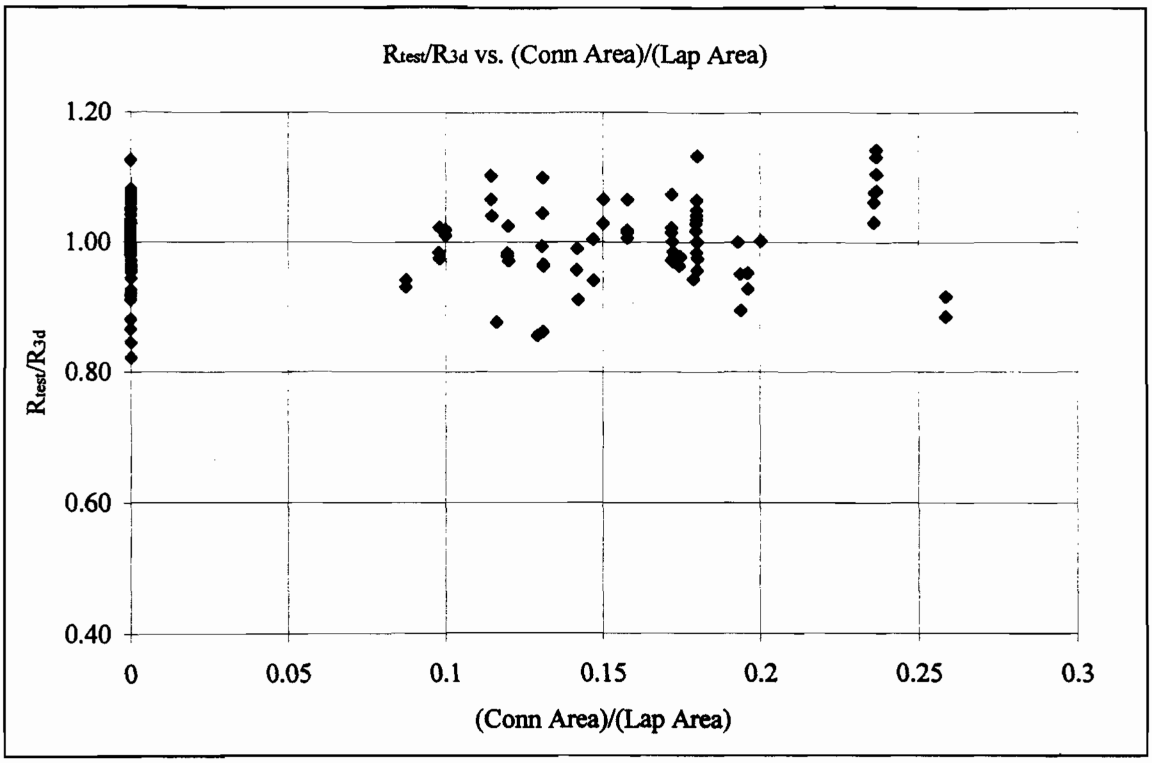


Figure 4.21 R_{test}/R_{3d} vs. Ratio of Connection Area to Lapped Sheet Area

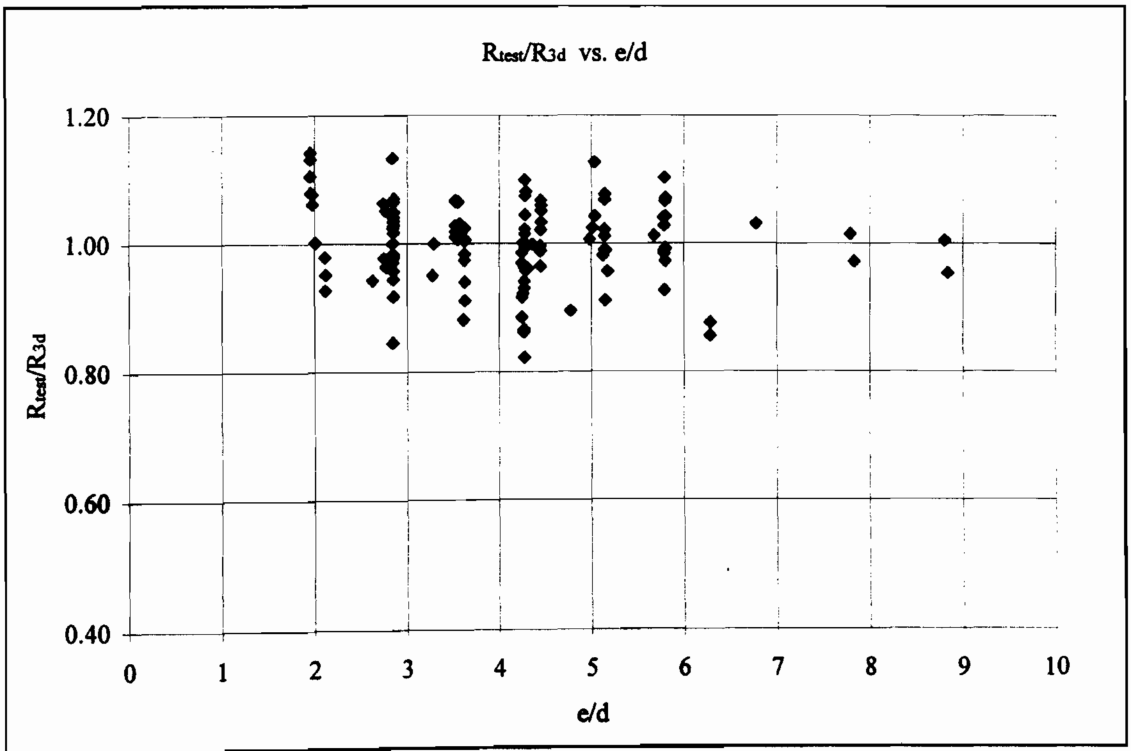


Figure 4.22 R_{test}/R_{3d} vs. Ratio of Transverse Edge Distance to Nominal Screw Diameter

The center-to-center spacing of the screw did influence the connection performance. The 2d screw spacing gave a greater "Group Effect" than 3d screw spacing. The graph for the 2d spacing "Group Effect" is given by Figure 4.23.

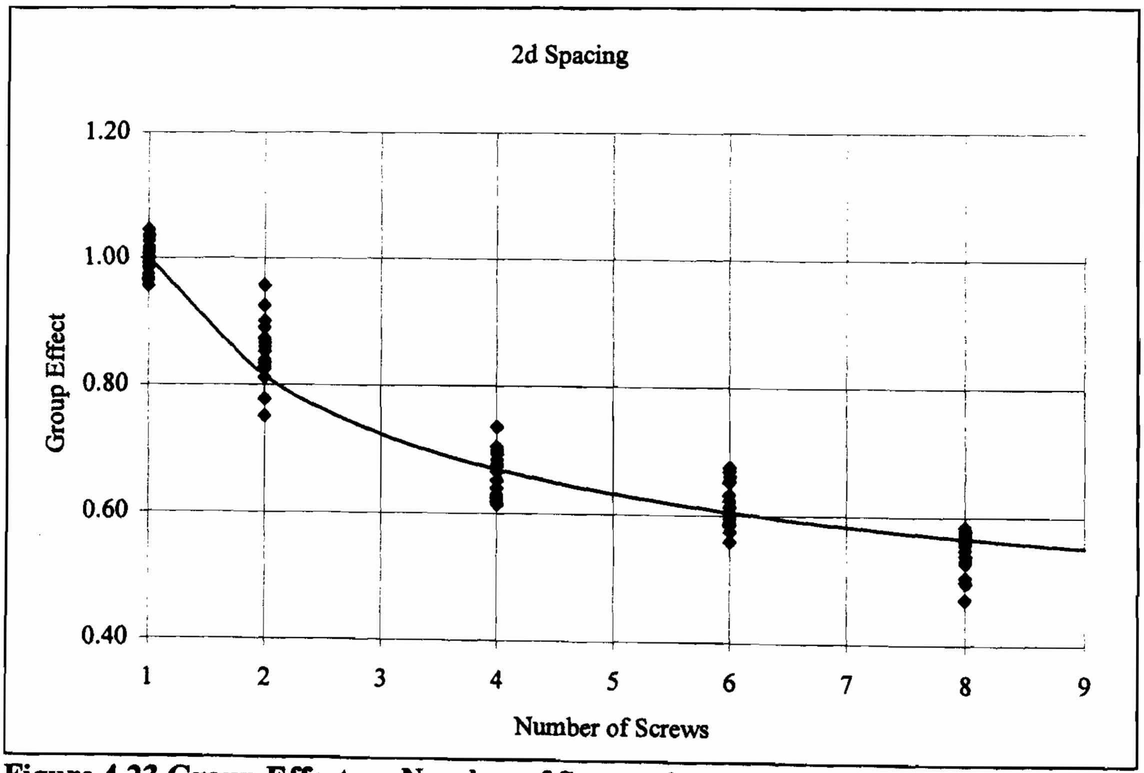


Figure 4.23 Group Effect vs. Number of Screws for 2d Spacing

The best fit curve for Figure 4.23 is given as Equation (4-4).

$$R_{2d} = \left(0.318 + \frac{0.702}{\sqrt{n}}\right) \leq 1.0 \qquad (4\text{-}4)$$

where:

R_{2d} = reduction factor that accounts for the "Group Effect" for $s < 3d$

s = screw center-to-center spacing

d = nominal screw diameter

n = number of screws in connection

Dividing Equation (4-3) by Equation (4-4) gives the curve in Figure 4.24. This figure indicates that the center-to-center spacing of the screws could influence the capacity by as much as 20%.

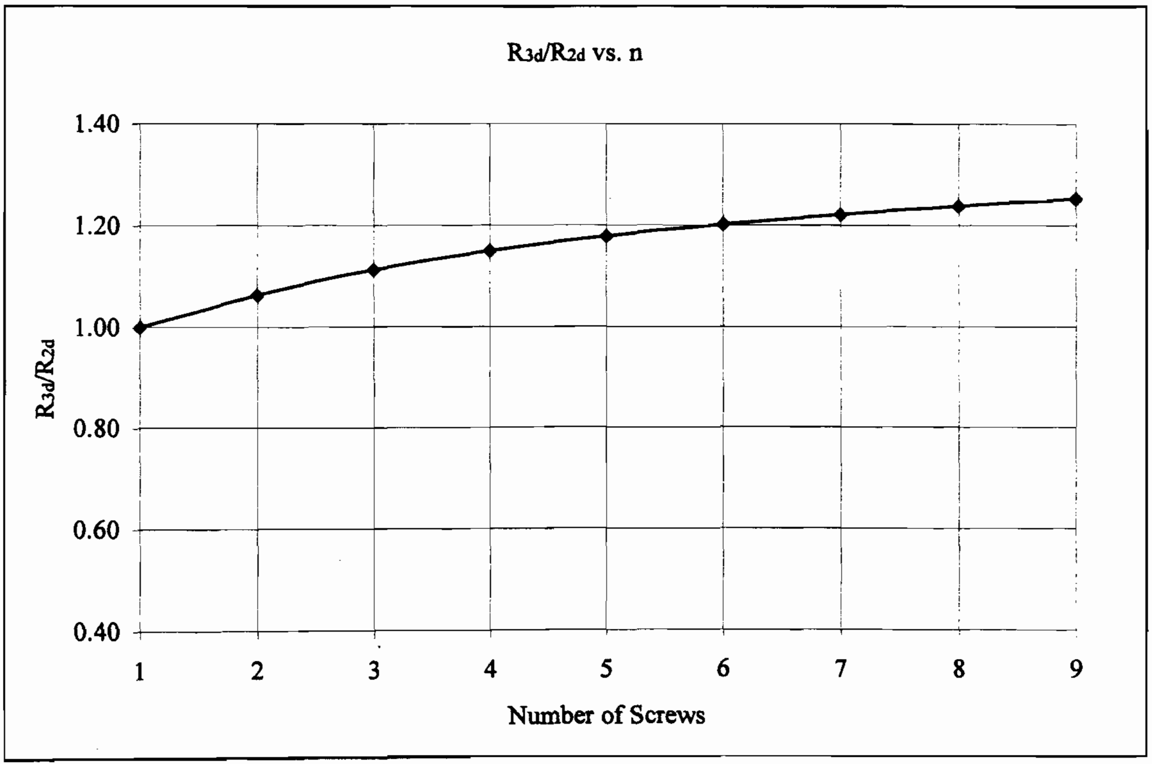


Figure 4.24 R_{3d}/R_{2d} vs. Number of Screws

The best fit curve for Figure 4.24 is given as Equation (4-5).

$$R_M = 0.697 + \frac{0.330}{\sqrt{n}} \tag{4-5}$$

where:

R_M = reduction factor that modifies 3d spacing to 2d spacing effect

s = screw center-to-center spacing

d = nominal screw diameter

n = number of screws in connection

Given the above equations, two possible sets of design equations are proposed. The first design model is given in Equations (4-6) through (4-9), the second design model is given in Equations (4-10) through (4-14).

Design Model 1:

$$P = nP_1R \tag{4-6}$$

where:

n = number of screws in a connection

P_1 = strength for a single screw connection = $F_u td\left(2.013\frac{t}{d} + 1.56\right)$ (4-7)

R = reduction factor for the connection "Group Effect"

for $s \geq 3d$, $R = R_{3d}$ $\quad R_{3d} = \left(0.535 + \frac{0.467}{\sqrt{n}}\right) \leq 1.0$ (4-8)

for $2d < s < 3d$, $R = R_{2d}$ $\quad R_{2d} = \left(0.318 + \frac{0.702}{\sqrt{n}}\right) \leq 1.0$ (4-9)

F_u = ultimate tensile strength of steel sheets being joined

t = thickness of sheets being joined

d = nominal screw diameter

s = center-to-center spacing of the screws

Design Model 2:

If $s \geq 3d$, $P = nP_1R_{3d}$ (4-10)

If $2d < s < 3d$, $P = nP_1R_{3d}R_M$ (4-11)

where:

n = number of screws in a connection

P_1 = strength for a single screw connection = $F_u td\left(2.013\frac{t}{d}+1.56\right)$ (4-12)

R_{3d} = reduction factor for the connection "Group Effect" for 3d spacing

$$R_{3d} = \left(0.535+\frac{0.467}{\sqrt{n}}\right) \leq 1.0 \tag{4-13}$$

R_M = reduction factor that modifies 3d spacing to 2d spacing effect

$$R_M = 0.697+\frac{0.330}{\sqrt{n}} \tag{4-14}$$

F_u = ultimate tensile strength of steel sheets being joined

t = thickness of sheets being joined

d = nominal screw diameter

s = center-to-center spacing of the screws

These design models are compared with the data found in this study, as well as the data of Daudet (1996), and Rogers and Hancock (1997). The current AISI equations (AISI, 1996) are also evaluated for the same data. P_{test}/P_{calc} is calculated, where P_{test} is the actual connection strength and P_{calc} is calculated using the two proposed design models, as well as AISI design equations. Values for the mean of P_{test}/P_{calc} are shown in Table 4.10 (the complete set of P_{test}/P_{calc} for all data is given in Appendix N). Table 4.11 gives coefficients of variation for P_{test}/P_{calc}. Table 4.12 gives the calculated resistance factor (ϕ) for LRFD design. Table 4.13 gives the calculated factor of safety (Ω) for ASD. "All" refers to all data being considered together. Breakdowns by 2d and 3d spacing are also shown.

Table 4.10 Comparison of Mean for P_{test}/P_{comp}

Data	Number of Data Points	Design Model 1 Mean	Design Model 2 Mean	AISI Mean
All	353	1.08	1.08	0.96
Sokol 3d	128	1.01	1.01	0.86
Sokol 2d	72	1.02	1.02	0.70
Sokol All	200	1.02	1.02	0.80
Rogers & Hancock	12	1.32	1.32	1.41
Daudet	141	1.15	1.15	1.14
All 2d	81	1.04	1.05	0.74
All 3d	272	1.09	1.09	1.02

For both design models, Table 4.10, it is seen that there is a large deviation from 1.0 for the mean values for Rogers and Hancock. One reason for this could be that the spacing of screws in the connection ranged from 4.4d to 5.7d. It has already been discussed in this study that the calculated strength for 2d spacing was less than that for 3d spacing. Equations were developed for spacings less than 3d, and for spacings greater than or equal to 3d. If equations were developed that took 4d or greater spacing into account, it is thought that larger calculated strengths would be found. The large P_{test}/P_{calc} ratio encountered in the Rogers and Hancock data supports this hypothesis. For all data, the AISI design equations provided an acceptable P_{test}/P_{calc} mean of 0.96, however the coefficient of variation was 0.26.

Table 4.11 Comparison of Coefficient of Variation for P_{test}/P_{comp}

Data	Number of Data Points	Design Model 1 COV	Design Model 2 COV	AISI COV
All	353	0.14	0.14	0.26
Sokol 3d	128	0.06	0.06	0.15
Sokol 2d	72	0.07	0.07	0.19
Sokol All	200	0.06	0.06	0.19
Rogers & Hancock	12	0.22	0.22	0.21
Daudet	141	0.15	0.15	0.15
All 2d	81	0.10	0.10	0.23
All 3d	272	0.15	0.15	0.23

Table 4.12 Summary of Phi Factor (ϕ)

Data	Model 1	Model 2	AISI
All	0.65	0.65	0.44
Sokol 3d	0.67	0.67	0.50
Sokol 2d	0.67	0.67	0.38
Sokol All	0.67	0.67	0.44
Rogers & Hancock	0.63	0.63	0.68
Daudet	0.68	0.68	0.67
All 2d	0.67	0.67	0.36
All 3d	0.64	0.64	0.51

Table 4.13 Summary of Factor of Safety (Ω)

Data	Model 1	Model 2	AISI
All	2.47	2.47	4.80
Sokol 3d	2.39	2.39	4.56
Sokol 2d	2.39	2.38	5.92
Sokol All	2.38	2.38	5.16
Rogers & Hancock	2.56	2.56	4.57
Daudet	2.36	2.36	3.29
All 2d	2.40	2.40	4.39
All 3d	2.49	2.49	3.13

4.10 PHI FACTOR AND FACTOR OF SAFETY

Derivation of the phi factor ,Φ, and factor of safety, Ω, for use in LRFD and ASD design equations is based on Chapter F of the Specification for the Design of Cold-Formed Steel Structural Members (AISI, 1996). Φ is defined by Equation (4-15). A sample calculation is given for the "all" data entry given in Tables 4.10 through 4.13, for Design Model 1.

$$\phi = 1.5(M_m F_m P_m) e^{-\beta_0 \sqrt{V_M{}^2 + V_F{}^2 + C_P V_P{}^2 + V_Q{}^2}} \qquad (4\text{-}15)$$

where:

M_m = mean value of material factor, M, from AISI Table F1 for screw connections = 1.10

F_m = mean value of fabrication factor, F, from AISI Table F1 for screw connections = 1.00

P_m = mean value of the professional factor, P, for the tested component = 1.08

β_0 = target reliability index = 3.5 for connections

V_M = coefficient of variation of the material factor, from AISI Table F1 for screw connections = 0.10

V_F = coefficient of variation of the fabrication factor, from AISI Table F1 for screw connections = 0.10

C_P = correction factor = $\left(1+\frac{1}{n}\right)\frac{m}{m-2}$ for $n \geq 4$

where:

n = number of tests = 353

m = degrees of freedom = n -1 = 352

$$\text{therefore } C_P = \left(1+\frac{1}{353}\right)\frac{352}{352-2} = 1.009$$

V_P = coefficient of variation of the test results (not less than 0.065)

= 0.14 > 0.065, therefore use 0.14

V_Q = coefficient of variation of the load effect = 0.21

e = natural logarithmic base = 2.718

therefore:

$\Phi = 0.65$

Ω is defined in Equation (4-16).

$$\Omega = \frac{1.6}{\phi} \qquad (4\text{-}16)$$

This gives $\Omega = 2.47$.

4.11 DESIGN MODEL LIMITATIONS

The design models presented are limited by the following parameters:

$0.030 \text{ inch} \le t \le 0.053 \text{inch}$

$0.165 \text{ inch} \le d \le 0.215 \text{ inch}$

$2d \le s \le 3.25d$

$47 \text{ ksi} \le F_u \le 70 \text{ ksi}$

$$1.19 \le \frac{F_u}{F_y} \le 1.62$$

5. CONCLUSIONS

5.1 STANDARD TEST

Screw strength can depend on screw profile (head type (e.g. hex, flat), drive configuration (e.g. Phillips, Torx), thread series, and size), specified grade, and washer and/or sealant used. For short screws, a correlation is provided between tensile strength and the torque required to twist off the head of the screw.

A standard test method for testing self-drilling screws was created. This method addressed testing screws in tension, shear, combined tension and shear, and a torque-tension correlation for screws too short to be tension tested. Limited testing was performed to ascertain the consistency and practicality of different methods of screw testing.

For tension testing, two methods were devised. The first involved a two-piece fixture, one piece that allowed the head to be supported, the other grasped the threads. The second method involved using the grips of the tension testing machine to grasp the threads directly. Both test methods produced comparable tested tension strength.

For shear testing, two methods were devised. The first method used thick plates that overlapped. The plates contained holes for inserting one or two screws to be tested. The main problem with this fixture was that it allowed significant screw tilting and inconsistent results. The second method used sheet steel as a disposable fixture. The self-drilling screws connected two pieces of sheet steel together in a lap connection. This assembly more accurately resembled the conditions that a screw would see in a connection and provided consistent results. The sheets had to be thick enough to prevent bearing and tilting failures.

The combined tension and shear test involved two methods also. The first method employed the same tension testing fixture used for tension tests, except that the fixture was inserted into the tension testing machine at an angle. The second method was developed by Luttrell, and involved a section of steel deck fastened to a channel. This assembly was placed into a loading frame which could be adjusted to an angle of interest to load the screw in combined tension and shear. No tests were run in this study using Luttrell's method.

Finally, a torque-tension correlation was developed for screws too short to be tested in tension. The torque test involved clamping a screw in a vice and twisting the head of the screw using a calibrated torque wrench. The ratio of failure torque to screw tensile strength was found to be 0.035 in-lb/lb. An alternate method was presented that involved finding an average hardness for the screw cross section (case hardening causes the screw hardness to be variable). This hardness could then be related to the screw tensile strength.

A test procedure was written in language appropriate for adoption as a standard.

5.2 CONNECTION STRENGTH

Lap connections were tested in which the parameters that varied were sheet thickness, screw size, screw pattern, number of screws, screw spacing, and stripped screws. The focus was on bearing failures. As was already well established, thicker sheets and larger screws give larger bearing capacities.

The main conclusions are that screw pattern does not cause a significant variation in strength. Also, the number of screws does not give a direct multiplier of strength when compared to single-screw strength. For example, a connection with 4 screws may only be

3 times stronger than a connection with one screw. Also, varying the spacing of the screws impacts the strength, as well as diminishing the multiplier of single-screw strength.

All specimens experienced rotation at the connection (due to tilting of screws). This meant that bearing failures were actually a combination of tilting, bearing, and then tearing or fracture (if there are few screws, tearing tends to occur; for large numbers of screws, fracture between screw holes occurs). Fracture was a combination of bending and tension in the sheet. Shear was a combination of shear and tension on the screw.

Even though thicker material gives greater bearing capacity, by looking at the "group effect" graphs, on thinner material, there is less reduction of screw strength with additional screws. This means that each screw is participating more equally (normally the screws at the ends of the connection work harder than the rest). This may be because the thin material distorts more easily, and thus causes the load to be distributed more equally.

Screw pattern had an effect, but one that was so minimal as to be negligible. The effect was that more rows gives more strength in lap connections, probably due to adding rotational stiffness to the connection. This effect is limited to patterns that take up most of the sheet width, as it was found that lower strengths occurred when the screw pattern was narrow as compared to the sheet width. It is recommended that pattern be ignored in strength calculations as it adds or subtracts minimally to the connection strength.

As the number of screws in a connection increases, the strength increases, but not as a direct multiple of the single screw strength. That is, a connection with 4 screws is not 4 times as strong as a connection with one screw. The amount that each additional screw adds to the connection strength is constant, as seen by the straight line in the graphs in Appendices H, I, and J (Connection Graphs).

Screw spacing has a direct impact on the connection strength. 2d and 3d spacings were investigated. The larger the spacing the greater the strength that occurred. At 2d and 3d spacings, the connection strength still has a linear relationship to the number of screws.

Stripped screws had no measurable effect on connection strength.

A design equation was developed which was statistically better than the present AISI design equation, when applied to the connections in this study.

6. FUTURE RESEARCH SUGGESTIONS

6.1 STANDARD TEST

If a standard tension test fixture could be developed for use industry-wide, this would help make objective comparison of manufacturer's screws possible. A test fixture that allowed a variety of screw sizes (thread pitch, shank diameter, head type) would be ideal.

In this study, the use of a pre-drilled shear fixture did not yield reliable, consistent results. Alternatives could include creating a double shear fixture to prevent screw tilting, using hardened material for a fixture to prevent fixture damage and deformation, and creating threads in the fixture that allowed the screws to be snug when screwed into the fixture. Another solution could be to create a threaded block for the threads to be secured into, such that the block would be snug up against one fixture face, just as the screw head was snug against the opposite fixture face. The disadvantage with most of these alterations was that the universality of the test fixture is lost, i.e. a separate fixture is required for each screw thread series and diameter tested.

More work is required on the combined tension and shear test, perhaps to find a test that is even simpler and more universal, and one that gives more reliable values.

More work needs to be done on the torque/tension correlation. Perhaps the correlation will be a function of screw parameters, rather than just being constant regardless of the screw.

6.2 CONNECTION STRENGTH

It may be argued that the data presented in the connection strength graphs may actually fit a parabolic shape, with the data for larger number of screws starting to taper off. This may be occurring because at higher numbers of screws in a connection, larger capacities are reached, and the sheet is approaching its fracture strength. Perhaps, therefore, the failures are a combination of fracture of the sheet and bearing of the screw on the sheet, which could cause a leveling off of the data. More connection tests could be run, with larger numbers of screws and stronger or larger sheets to determine this effect.

More rows of screws gave more strength due to rotational stability. Is there a limit to this increase? An area worth researching could be the effect of edge stiffeners on the sheets that are being tested. These stiffeners could provide better rotational stability than increased rows of screws. This may change the effect of adding rows of screws.

Spacings larger than 3d should be studied, and perhaps even spacings between 2d and 3d. Is there a limit to spreading out screws and getting a larger connection strength?

The tensile strength of the sheets could be a factor in the effect of strength increase with additional screws. Tests of connections that vary the tensile strength, while keeping other factors constant could be revealing as to whether this is a factor. Also, a study of low ductility sheet would be worthwhile.

In the screw patterns used, sometimes there were more screws at one end of the connection than at the other. Because the line through which fracture usually is on the sheet that has the screw threads protruding from it, patterns that are inverted versions of those that already exist could be tested.

Tests were run at a one stroke rate. Other tests could be run that vary the rate of loading, to see the effect load rate has on connection strength.

When sheets are wide and screws are grouped near the middle of the longitudinal centerline, the sheet cups around the connection. Would the connection strength be increased if the screws were spread out? What if screws were placed near the corners of the sheet in the connection?

Screws are put into sheets using a screw gun that has a torque setting (to prevent stripping of screws). The screw gun has variable speed. Does the speed that the screws are turned (for drilling the holes) impact the bearing resistance of the steel sheet near the screw (due to the heat generated)?

Additional work could also be performed on the effect of stripped screws on connection strength.

APPENDIX A

STANDARD TEST PROTOCOL

Standard Test Methods for Determining the Mechanical Properties of Screws

1. Scope

1.1 These test methods establish procedures for conducting tests to determine the mechanical properties of screws. The screws shall be thread-forming or thread-cutting, with or without a self-drilling point.

1.2 Property requirements and the applicable tests for their determination are specified in individual product standards. In those instances where the testing requirements are unique or at variance with these standard procedures, the product standard shall specify the controlling testing requirements.

1.3 These test methods describe mechanical tests for determining the following properties:

	Section
Axial Tension Testing of Full-Size Product	3.4
Single Shear Test	3.5
Combined Shear and Tension Test	3.6

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish* *appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

A 370 Standard Test Methods and Definitions for Mechanical Testing of Steel Products

E 4 Standard Practices for Force Verification of Testing Machines

E 10 Test Method for Brinell Hardness of Metallic Materials

E 18 Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials

F 606 Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets.

2.2 *AISI Documents:*

Test Methods for Mechanically Fastened Cold-Formed Steel Connections

3. Test Methods - A test series shall be conducted on each screw profile (head type (e.g. hex, flat), drive configuration (e.g. Phillips, Torx), thread series, and size), specified grade, and washer and/or sealant used.

3.1 *Torsion Tests* - This test is intended to determine the ability of a screw to withstand a predetermined load when applied about the axis of the screw. The test shall be performed by securing the thread end of the screw so that it may not rotate, ensuring that the threads are not crushed. A calibrated torque measuring device shall apply torque to the screw at the head of the screw. Torque required to twist the screw to failure shall be the torsion strength.

3.2 *Tension Tests* - This test is intended to determine the ability of a screw to withstand a predetermined load when applied along the axis of the screw.

3.2.1 It is required that screws be tested full size, and it is customary, when so testing, to specify a minimum ultimate load (or stress) in pounds-force (or pounds-force per square inch).

3.3 *Screws Too Short for Tension Testing* - Product lengths that do not have sufficient threads for proper engagement and still leave complete threads exposed between the grips, shall be deemed too short for tension testing, and acceptance shall be based on a torsion test. If tests other than the torsion test are required, their requirements should be referenced in the product specification. Tensile strength shall be taken as torsion strength divided by 0.035 in-lb/lb.

3.4 *Axial Tension Testing of Full-Size Product:*

3.4.1 Test screw in a holder with the load axially applied between the head and a suitable fixture, either of which shall have sufficient thread engagement to develop the full strength of the product. A sample test setup is shown in Figure 1. (Note: Threads may be clamped directly by jaws of testing machine if screw shank is not crushed in so doing.)

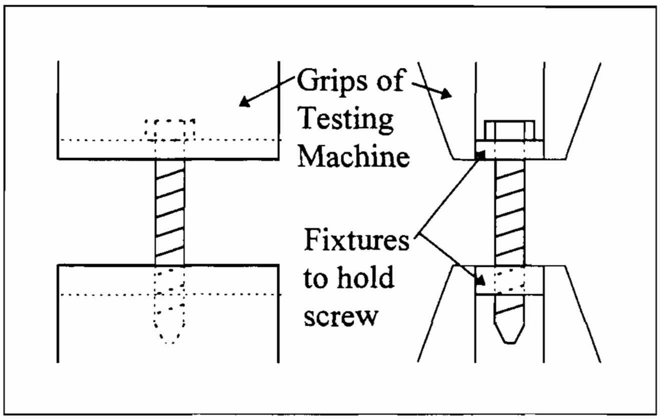


Figure A.1 Standard Tension Test

3.4.2 To meet the requirements of the test described in 3.4.1, the product shall support a load prior to fracture not less than the minimum tensile strength specified in the product specification for its head type, drive configuration, thread series, size, washer and/or sealant, and strength.

3.4.3 The speed of testing as determined by the rate of separation of the testing machine heads shall be limited to the greater of 0.1 in (2.5 mm) per minute or the rate caused by a loading rate of 500 pounds (approximately 2 kN) per minute.

3.4.4 The maximum load applied to the specimen, coincident with or prior to screw failure, shall be recorded as the tensile strength of the screw. At the discretion of the testing agency, tests need not be continued to destruction provided that the specimen supports, without evidence of screw failure, the minimum load specified.

3.5 *Single Shear Test* - This test is intended to determine the ability of a screw to withstand a predetermined load when applied transversely to the axis of the screw.

3.5.1 The specimen shall be tested using steel plates of sufficient thickness to preclude bearing failure. Shear plates shall create a single-lap joint using two flat straps connected with one or two fasteners. (If two fasteners are used, the total shear strength of the connection may be divided by two to determine the shear strength for one screw.) Suggested geometrical proportions of the test specimen are as given in Table 1, with reference to Figures 2 and 3. The test fixture shall provide for central loading across the lap joint. When the machine grips are adjustable or when the thickness of either strap is less than 1/16 in. (approximately 2 mm), packing shims are not required for central loading.

Table A.1 Suggested Geometrical Proportions - Specimen Dimensions

Screw Diameter inch (mm)	w	L	e	p
≤ ¼ (6.5)	2 (60)	10 (260)	1 (30)	2 (60)

3.5.2 The test specimen may be assembled in a shear jig or threaded into two flat sheets. The test specimen shall be mounted in a tensile-testing machine capable of applying load at a controllable rate. The grips shall be self-aligning and care shall be taken when mounting the specimen to assure that the load will be transmitted in a straight line transversely through the test screw(s). Load shall be applied and continued until failure of the screw(s). Speed of testing as determined by the rate of separation of the testing machine heads shall be limited to the greater of 0.1 in. (2.5 mm) per minute or the rate caused by a loading rate of 500 pounds (approximately 2 kN) per minute.

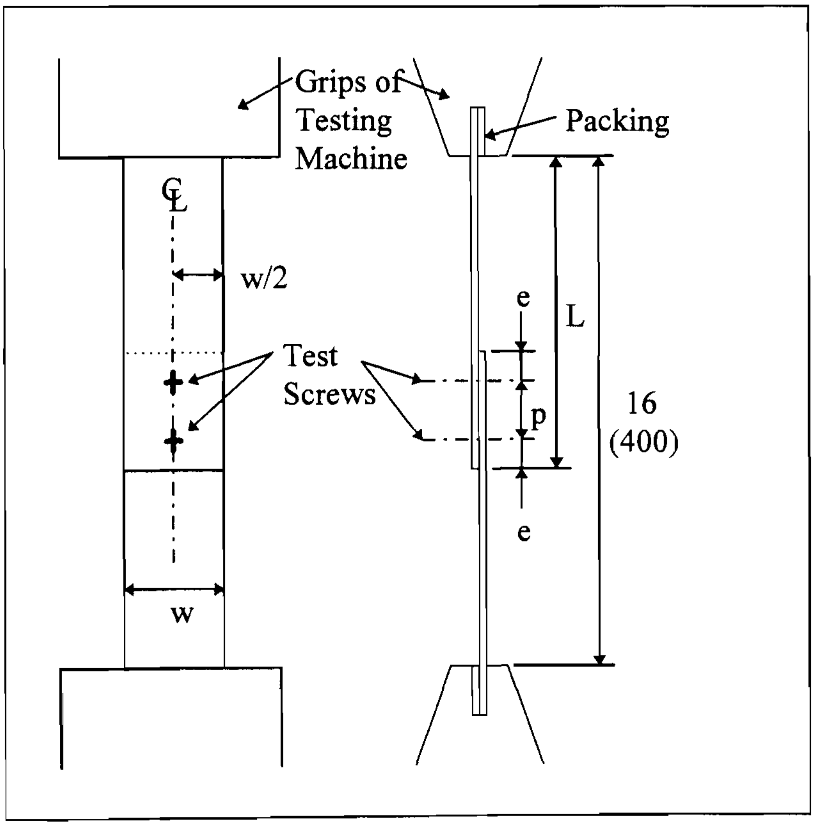


Figure A.2 Standard Lap-Joint Shear Test - 2 Screws

3.5.3 The maximum load applied to the specimen, coincident with or prior to screw failure, shall be recorded as the shear strength of the screw. At the discretion of the testing agency, tests need not be continued to destruction provided that the specimen supports, without evidence of screw failure, the minimum load specified.

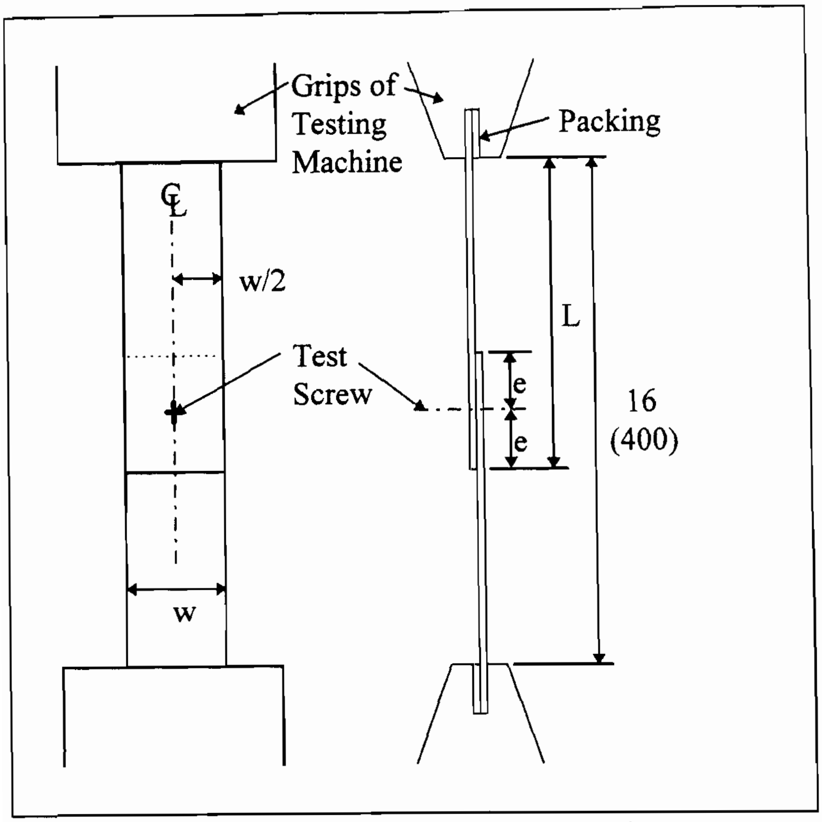


Figure A.3 Standard Lap-Joint Shear Test - 1 screw

3.6 *Combined Shear and Tension Test* - This test is intended to determine the ability of a screw to withstand a predetermined load that, when applied at an angle to the axis of the screw, creates a combined shear and tension force in the screw.

3.6.1 Test screws in a holder with the load applied between the head and a suitable fixture, either of which shall have sufficient thread engagement to develop the full strength of the product. A sample test setup is shown in Figure 4, with an alternate setup shown in Figures 5, 6, and 7.

3.6.2 To meet the requirements of the test described in 3.6.1, the product shall support a load prior to fracture not less than the minimum combined shear and tension strength specified in the product specification for its head type, drive configuration, thread series, size, washer and/or sealant, and strength.

3.6.3 The speed of testing as determined by the rate of separation of the testing machine heads shall be limited to the greater of 0.1 in (2.5 mm) per minute or the rate caused by a loading rate of 500 pounds (approximately 2 kN) per minute.

3.6.4 The maximum load applied to the specimen, coincident with or prior to screw failure, shall be recorded as the combined shear and tensile strength of the screw. At the discretion of the testing agency, tests need not be continued to destruction provided that the specimen supports, without evidence of screw failure, the minimum load specified.

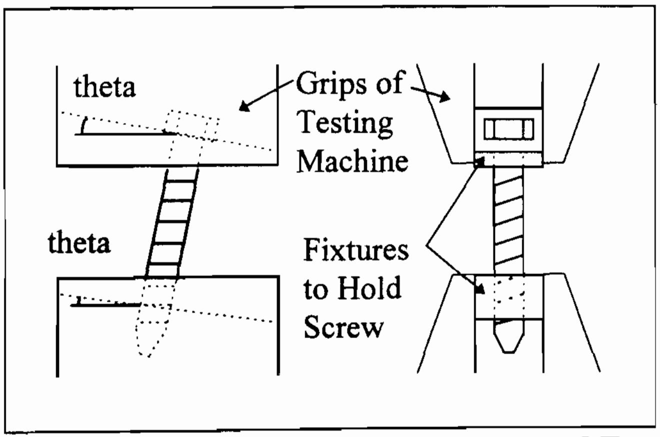


Figure A.4 Standard Combined Shear and Tension Test

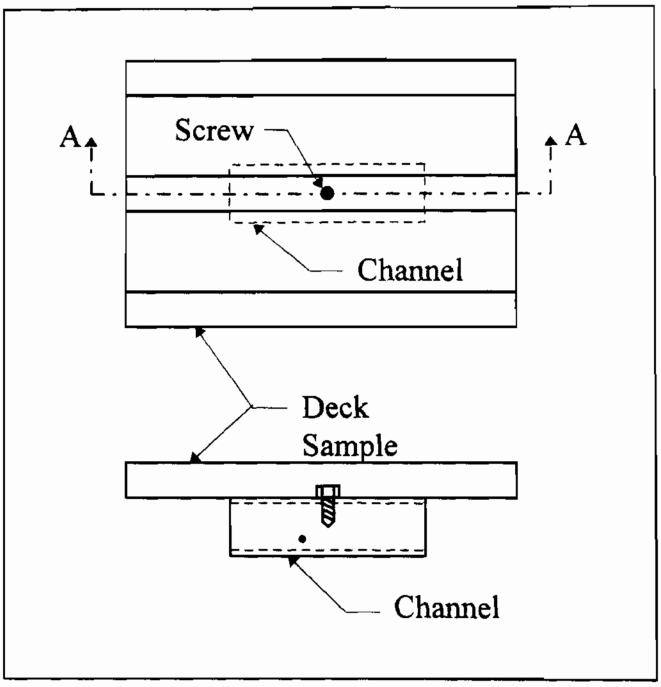


Figure A.5 Alternate Combined Shear and Tension Test - Deck Assembly

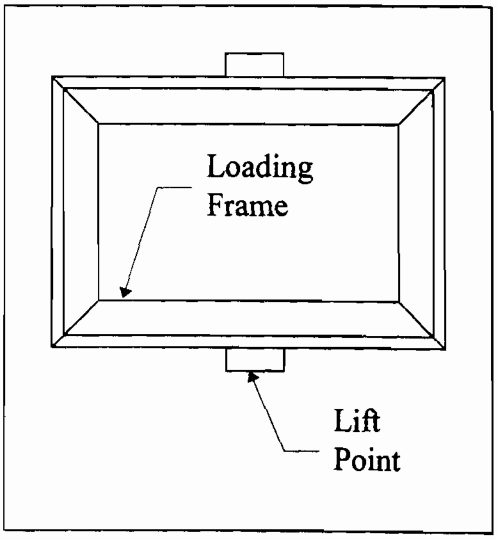


Figure A.6 Alternate Combined Shear and Tension Test - Loading Frame

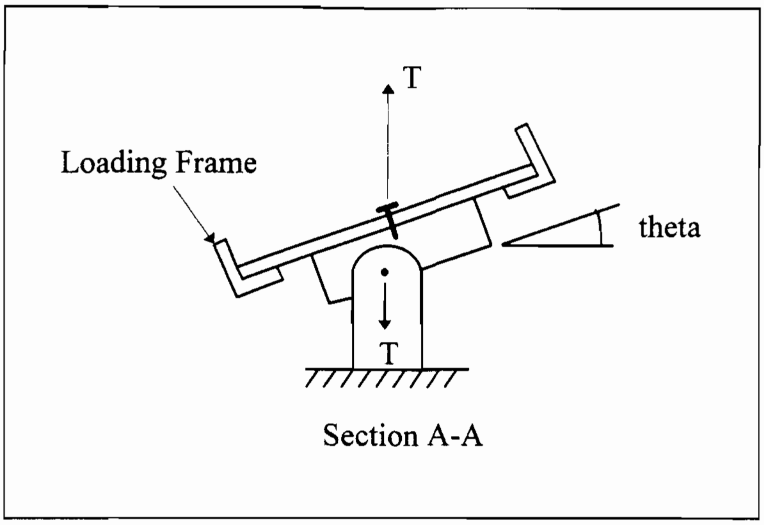


Figure A.7 Alternate Combined Shear and Tension Test - Test Setup

4. Report

4.1 The objectives and purposes of the test series shall be stated at the outset of the report so that the necessary test results such as the maximum load per fastener, the flexibility of the connection, and the mode of failure are identified.

4.2 The type of tests, the testing organization, and the dates on which the tests were conducted shall be included in the documentation.

4.3 The test unit shall be fully documented, including:

1. the measured dimensions of each specimen (e.g., thread O.D., thread I.D., threads per inch, head dimensions, screw length, etc.),
2. identification data for the screws and accessories such as washers (screw data shall include the name of the manufacturer, designation or type, dimensions,

number of threads, unthreaded length or imperfect threads below head, and the major and minor diameters in the threaded region),

3. the details of fastener application including predrilling, tightening torque, and any unique tools used in the operation, and
4. Additional data shall indicate the drill-point diameter and length of flutes if self-drilling screws are used. Otherwise, the diameter of the pilot drill used shall be stated. Washers or washer-head data shall include diameter, thickness, material, and if present the sealant data.

4.4 The test set-up shall be fully described including the testing machine, the specimen end grips or supports.

4.5 The test procedure shall be fully documented including the rate of loading and the load increments.

4.6 In accordance with the test objectives stated by the responsible engineer, the report shall include a complete documentation of all applicable test results for each specimen such as the load-deformation curve, the maximum load, and the mode of failure.

APPENDIX B

TEST FIXTURES FOR STANDARD TEST

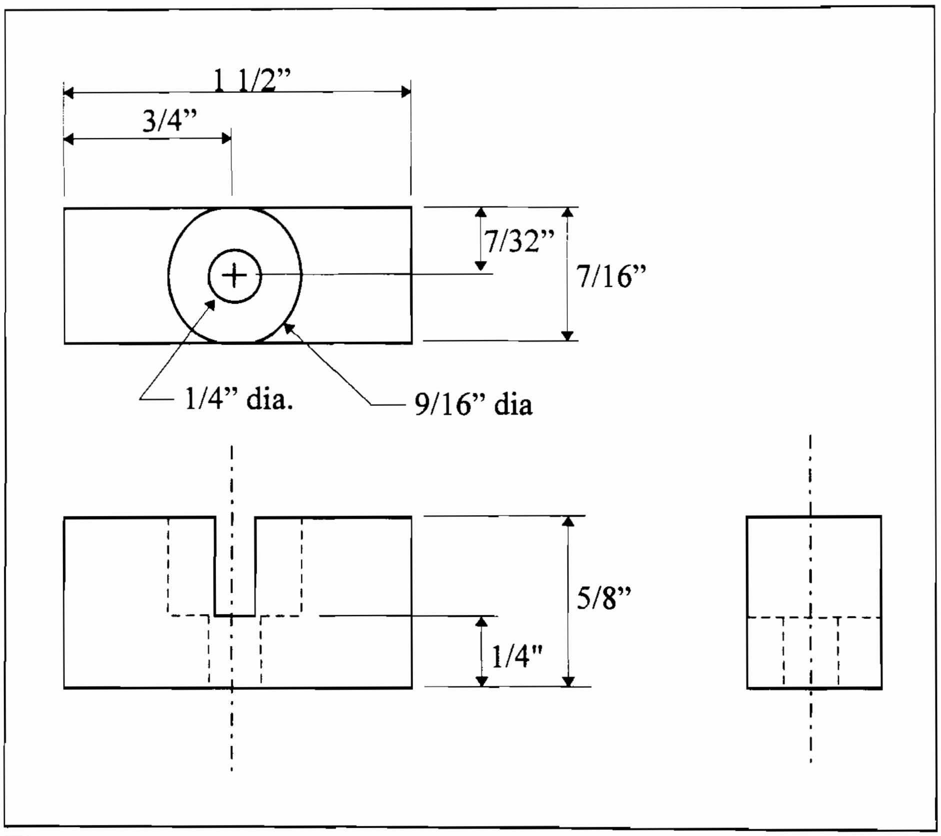


Figure B.1 Screw Tension Test - Top Fixture

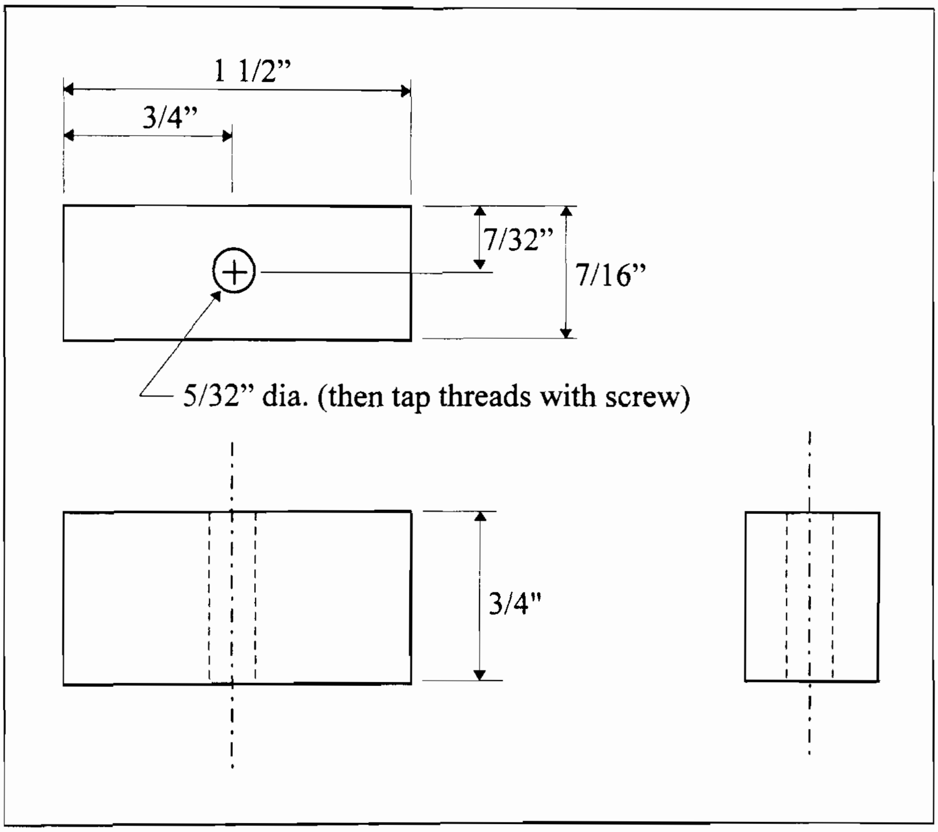


Figure B.2 Screw Tension Test - Bottom Fixture

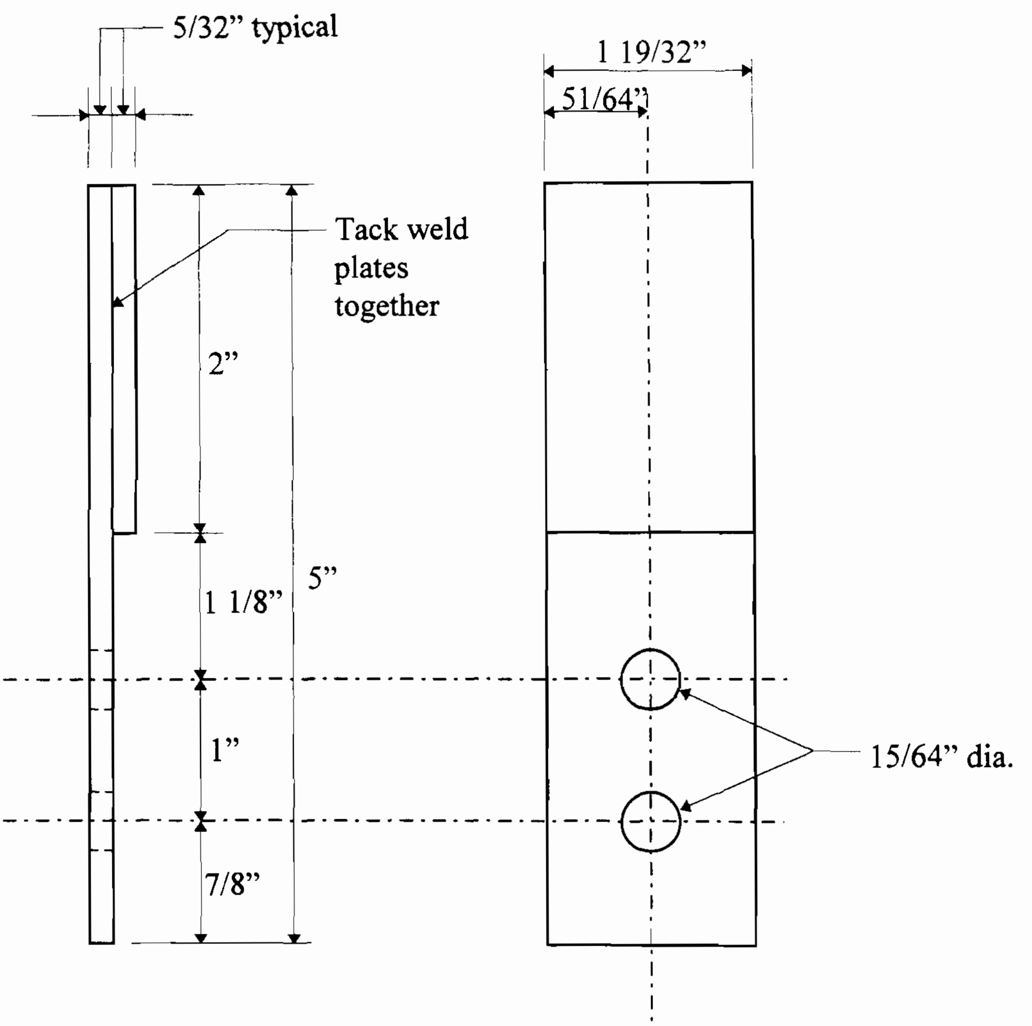


Figure B. 3 Screw Shear Test Fixture

APPENDIX C

TEST RESULTS FOR STANDARD TEST

Table C.1 Summary of Tension Tests (round head screws with square drive - #12-13x1-1/4)

Test #	Failure Load (lbs)	Rate: Stroke (in/min)
t1	3587	0.036
t2	2090	0.009
t3	3305	0.018
t4	2603	0.018
t5	2308	0.036
t6	3454	0.051
t7	1932	0.051
t8	2911	0.036
t9	2932	0.036

Table C.2 Summary of Tension Tests (blue #12-12x3" hex head screws)

Test #	Failure Load (lbs)	Rate: Stroke (in/min)
t10	2978	0.036
t11	3000	0.036
t12	3013	0.036
Avg.	2997	
COV	0.01	

Table C.3 Summary of Tension Tests (#10-16x1-1/2" Traxx hex head screws)

Test #	Failure Load (lbs)	Rate: Stroke (in/min)
t13	2818	0.1
t14	2799	0.1
t15	3160	0.1
t16	3187	0.1
t17	2468	0.1
Avg.	2886	
COV	0.10	

Table C.4 Summary of Tension Tests Using Fixture (#12-14x3" Traxx hex head screws)

Test #	Failure Load (lbs)	Rate: Stroke (in/min)
t18	3809	0.1
t19	3785	0.1
t20	4099	0.1
t21	3548	0.1
t22	4020	0.1
Avg.	3852	
COV	0.06	

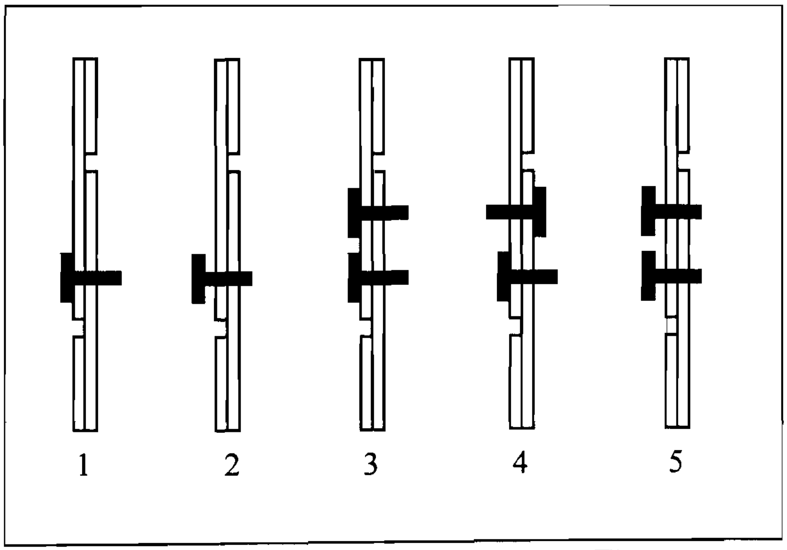


Figure C.1 Setups for Shear Testing Using Fixture

Table C.5 Summary of Shear Tests Using Fixture (round head screws with square drive)

Test #	Failure Load (lbs)	Setup #	Control: S = Stroke L = Load	Rate: Stroke (in/min) Load (lbs/min)
s1	2080	1	S	0.036
s2	2210 & 2490*	2	S	0.036
s3	1020	1	L	9400
s4	1460	1	L	330
s5	1000	1	L	330
s6	2100	2	L	330
s7	1860	3	L	330
s8	4120	4	L	330
s9	3680	4	S	0.018
s10	2670	5	S	0.18
s11	1980	5	S	0.18

* Two distinct peak loads attained - load sharing was minimal.

Table C.6 Summary of Shear Tests Using Lapped Sheet Steel

Test #	Failure Load (lbs)	# of Screws	Strength per screw (lbs)	Rate: Stroke (in/min)
s12	2973	2	1487	0.1
s13	3100	2	1550	0.1
s14	1534	1	1534	0.1
s15	1756	1	1756	0.1
s16	1590	1	1590	0.1

Note: #10-16x1-1/2" Traxx hex head screws. Sheet steel is 3' wide, 0.072" thick.

Table C.7 Torque Test (blue #12-12x3" hex head screws)

Test #	Failure Load (in-lbs)	Clamped Near:	Broke Near:
q1	95	top	head
q2	95	top	head
q3	95	bottom	head
q4	100	bottom	head
Avg.	96.25		
COV	0.03		

Table C.8 Torque Test (#10-16x1-1/2" Traxx hex head screws)

Test #	Failure Load (in-lbs)	Clamped Near:	Broke Near:
q5	90	top	head
q6	92.5	top	head
q7	82.5	bottom	head
q8	77.5	bottom	head
q9	87.5	top	head
q10	82.5	top	head
q11	90	top	head
q12	92.5	bottom	bottom
q13	87.5	bottom	bottom
q14	85	bottom	bottom
Avg.	86.75		
COV	0.06		

Table C.9 Torque Test (#12-14x3" Traxx hex head screws)

Test #	Failure Load (in-lbs)	Clamped Near:	Broke Near:
q15	132.5	top	bottom
q16	145	top	bottom
q17	135	top	bottom
q18	140	top	bottom
q19	140	top	bottom
q20	130	bottom	bottom
q21	130	bottom	bottom
q22	135	bottom	bottom
q23	140	bottom	bottom
q24	137.5	bottom	bottom
Avg.	136.5		
COV	0.04		

Table C.10 Combined Shear and Tension Test (#10-16x1-1/2" Traxx hex head screws)

Test #	Failure Load (lbs)	Angle from Vertical (degrees)	Rate: Stroke (in/min)
st1	3599	8	0.1
st2	3953	8	0.1
st3	3690	18	0.1
st4	2770	18	0.1

Table C.11 Tension Tests With and Without Bottom Fixture (#10-16x1-1/2" Traxx hex head screws)

Test #	Failure Load (lbs)	Using Bottom Fixture?	Rate: Stroke (in/min)
t23	3966	Y	0.1
t24	3886	Y	0.1
t25	3218*	N	0.1
t26	3837	N	0.1
t27	3664	N	0.1
t28	3878	N	0.1

* Jaws smashed threads in this test, causing premature failure.

APPENDIX D

SCREW AND SHEET MEASUREMENTS

The screws listed in Tables D.1 through D.4 were used in the Standard Test portion of this study. The tests in which they were used are listed in Appendix C. A sample of 10 screws was usually taken to get a representative value for the screw dimensions. The only exception to this is in Table D.1, where only 2 screws were available. The final line of the tables gives the average of all measured values.

A legend of the heading symbols follows (refer to Figures D.1 and D.2):

"Screw": gives screw number in the table.

"HT": head thickness.

"H": distance across flats of hex head screws.

"W": head washer diameter or head diameter on round head screws.

"d": thread outer diameter.

"TD": screw drill tip maximum diameter.

"L": screw length from bottom of head to end of screw tip.

"TL": approximate length of screw drill tip.

"TPI": screw threads per inch.

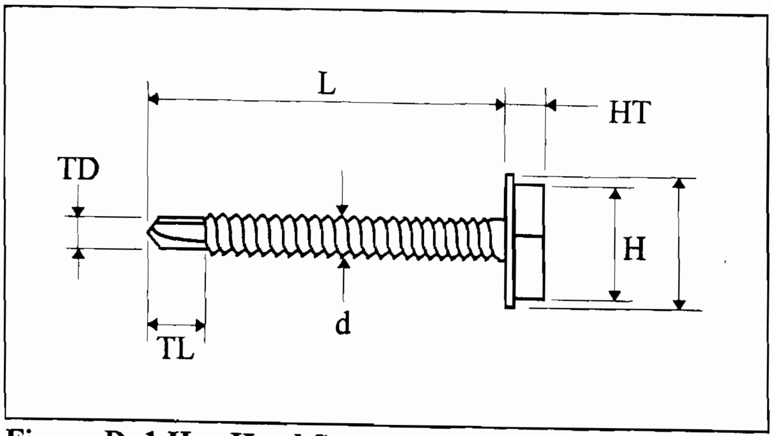


Figure D. 1 Hex Head Screw Dimensions

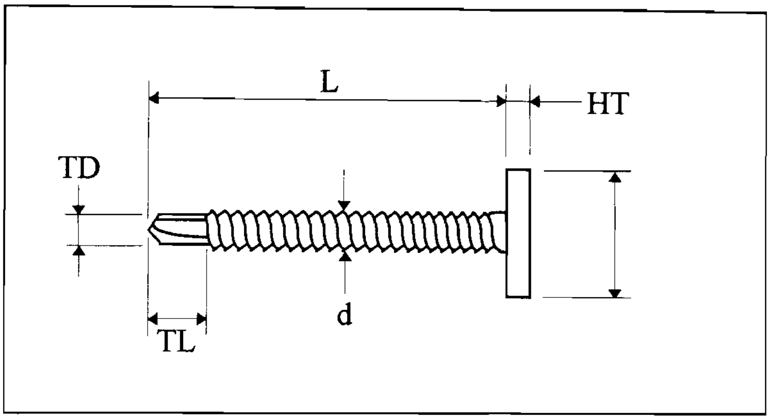


Figure D. 2 Round Head Screw Dimensions

Table D.1 Blue Hex Head #12-12 x 3

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.176	0.256	0.385	0.214	0.137	2.85	0.25	12.5
2	0.185	0.254	0.378	0.217	0.128	2.87	0.25	12.5
Avg.	**0.181**	**0.255**	**0.382**	**0.216**	**0.133**	**2.86**	**0.25**	**12.5**

Table D.2 Traxx Hex Head #10-16x1-1/2

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.149	0.309	0.394	0.185	0.157	1.47	0.31	16
2	0.147	0.308	0.404	0.187	0.159	1.47	0.31	16
3	0.149	0.309	0.397	0.185	0.155	1.47	0.31	16
4	0.152	0.308	0.398	0.187	0.158	1.46	0.31	16
5	0.138	0.308	0.414	0.187	0.149	1.46	0.31	16
6	0.138	0.308	0.398	0.187	0.149	1.47	0.31	16
7	0.136	0.309	0.405	0.186	0.151	1.47	0.31	16
8	0.148	0.311	0.402	0.185	0.161	1.46	0.31	16
9	0.149	0.308	0.401	0.185	0.160	1.47	0.31	16
10	0.150	0.308	0.401	0.185	0.159	1.47	0.31	16
Avg.	**0.146**	**0.309**	**0.401**	**0.186**	**0.156**	**1.47**	**0.31**	**16**

Table D.3 Traxx Hex Head #12-14x3

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.182	0.314	0.422	0.214	0.177	2.98	0.375	14
2	0.182	0.318	0.423	0.216	0.176	2.97	0.375	14
3	0.181	0.315	0.425	0.217	0.176	2.99	0.375	14
4	0.180	0.311	0.423	0.216	0.177	2.97	0.375	14
5	0.184	0.314	0.422	0.213	0.177	2.97	0.375	14
6	0.182	0.312	0.421	0.213	0.178	2.97	0.375	14
7	0.183	0.312	0.422	0.215	0.178	2.97	0.375	14
8	0.180	0.312	0.420	0.214	0.175	2.99	0.375	14
9	0.183	0.311	0.415	0.214	0.177	2.97	0.375	14
10	0.179	0.313	0.415	0.215	0.175	2.97	0.375	14
Avg.	**0.182**	**0.313**	**0.421**	**0.215**	**0.177**	**2.98**	**0.375**	**14**

Table D.4 Round head with square drive #12-13x1-1/4

Screw	HT (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.083	0.525	0.235	0.129	1.25	0.25	13
2	0.083	0.520	0.231	0.130	1.25	0.25	13
3	0.080	0.522	0.239	0.130	1.25	0.25	13
4	0.082	0.517	0.231	0.130	1.24	0.25	13
5	0.082	0.523	0.235	0.130	1.25	0.25	13
6	0.082	0.528	0.235	0.130	1.26	0.25	13
7	0.081	0.522	0.232	0.130	1.26	0.25	13
8	0.081	0.529	0.234	0.128	1.26	0.25	13
9	0.081	0.525	0.235	0.129	1.25	0.25	13
10	0.081	0.523	0.236	0.129	1.25	0.25	13
Avg.	**0.082**	**0.523**	**0.234**	**0.130**	**1.25**	**0.25**	**13**

Tables D.5 through D.8 are for screws used in the Connection Tests. The tests in which they were used are listed in Appendix F "Data for Connection Tests".

Table D.5 Dynamic Fastener Hex Head #8-18 x 3/4

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.129	0.249	0.330	0.165	0.140	0.75	0.21	17.5
2	0.130	0.248	0.331	0.165	0.137	0.73	0.21	17.5
3	0.140	0.249	0.328	0.165	0.134	0.74	0.21	17.5
4	0.138	0.248	0.334	0.166	0.136	0.75	0.21	17.5
5	0.128	0.249	0.340	0.166	0.138	0.74	0.21	17.5
6	0.127	0.250	0.330	0.165	0.135	0.74	0.21	17.5
7	0.140	0.248	0.334	0.166	0.134	0.73	0.21	17.5
8	0.133	0.249	0.328	0.166	0.135	0.73	0.21	17.5
9	0.133	0.249	0.326	0.165	0.135	0.75	0.21	17.5
10	0.131	0.249	0.330	0.165	0.135	0.73	0.21	17.5
Avg.	**0.133**	**0.249**	**0.331**	**0.165**	**0.136**	**0.74**	**0.21**	**17.5**

Table D.6 Dynamic Fastener Hex Head #10-16 x 3/4

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.140	0.308	0.400	0.186	0.153	0.74	0.25	15.5
2	0.144	0.308	0.402	0.186	0.155	0.73	0.25	15.5
3	0.141	0.310	0.402	0.186	0.154	0.73	0.25	15.5
4	0.140	0.310	0.403	0.186	0.153	0.73	0.25	15.5
5	0.142	0.307	0.402	0.186	0.156	0.74	0.25	15.5
6	0.140	0.314	0.401	0.186	0.156	0.74	0.25	15.5
7	0.142	0.309	0.405	0.185	0.155	0.74	0.25	15.5
8	0.136	0.310	0.402	0.187	0.154	0.73	0.25	15.5
9	0.140	0.310	0.403	0.186	0.154	0.73	0.25	15.5
10	0.141	0.309	0.392	0.186	0.155	0.74	0.25	15.5
Avg.	**0.141**	**0.310**	**0.401**	**0.186**	**0.155**	**0.74**	**0.25**	**15.5**

Table D.7 Dynamic Fastener Hex Head #12-14 x 3/4

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.182	0.312	0.411	0.216	0.176	0.72	0.35	14
2	0.181	0.312	0.417	0.215	0.178	0.73	0.35	14
3	0.179	0.313	0.416	0.215	0.177	0.73	0.35	14
4	0.181	0.313	0.417	0.213	0.177	0.73	0.35	14
5	0.182	0.312	0.411	0.216	0.177	0.73	0.35	14
6	0.182	0.312	0.419	0.215	0.178	0.73	0.35	14
7	0.181	0.312	0.411	0.216	0.177	0.73	0.35	14
8	0.181	0.313	0.417	0.216	0.178	0.73	0.35	14
9	0.182	0.314	0.418	0.216	0.178	0.73	0.35	14
10	0.178	0.312	0.418	0.216	0.177	0.73	0.35	14
Avg.	**0.181**	**0.313**	**0.416**	**0.215**	**0.177**	**0.73**	**0.35**	**14**

Table D.8 Grabber Hex Head #12-14 x 3/4 (part number X12075H3)

Screw	HT (in)	H (in)	W (in)	d (in)	TD (in)	L (in)	TL (in)	TPI
1	0.183	0.308	0.417	0.215	0.178	0.76	0.35	14
2	0.182	0.311	0.418	0.215	0.179	0.75	0.35	14
3	0.183	0.312	0.413	0.215	0.177	0.75	0.35	14
4	0.182	0.311	0.420	0.215	0.182	0.75	0.35	14
5	0.183	0.309	0.416	0.216	0.179	0.76	0.35	14
6	0.184	0.308	0.415	0.215	0.180	0.76	0.35	14
7	0.184	0.308	0.418	0.215	0.178	0.75	0.35	14
8	0.184	0.309	0.418	0.214	0.183	0.75	0.35	14
9	0.182	0.309	0.421	0.214	0.181	0.75	0.35	14
10	0.184	0.308	0.421	0.215	0.182	0.76	0.35	14
Avg.	**0.183**	**0.309**	**0.418**	**0.215**	**0.180**	**0.75**	**0.35**	**14**

Steel sheets used for the connection tests came in bundles of approximately 10 each. As each bundle was opened, the top sheet was measured, and is recorded below. Each test number includes the sheet bundle number ("N" indicates normal ductility steel, the second number gives the sheet gage, and the number following the dash gives the bundle number).

Table D.9 Sheet Dimensions by bundle

Sheet Bundle #	Width (in)	Thickness (in)
N16-1	1.914	0.053
N16-2	1.912	0.053
N16-3	1.913	0.053
N16-4	1.853	0.053
N16-50	2.905	0.053
N16-51	2.911	0.053
N16-52	2.901	0.053
N16-53	2.907	0.053
N18-1	1.913	0.040
N18-2	1.913	0.040
N18-3	1.911	0.040
N18-4	1.865	0.040
N18-50	2.913	0.040
N18-51	2.912	0.040
N18-52	2.915	0.040
N20-1	1.910	0.030
N20-2	1.909	0.030
N20-3	1.908	0.030
N20-4	1.873	0.030
N20-5	1.875	0.030
N20-50	2.904	0.030
N20-51	2.901	0.030
N20-52	2.905	0.030
N20-53	2.905	0.030
N20-54	2.898	0.030

APPENDIX E

STRESS-STRAIN GRAPHS FOR CONNECTION TESTS

ASTM A 370-97a, "Standard Test Methods and Definitions for Mechanical Testing of Steel Products" (ASTM, 1997) was adhered to in the specimen testing below.

Table E.1 Summary of Sheet Properties

Sheet & Specimen	Thickness (in)	Avg. Width (in)	Area (in^2)	2" length after test (in)	% elong	Fy (ksi)	Fu (ksi)
N16 #2	0.053	0.740	0.039	2.724	36.2	59	70
N16 #3	0.053	0.739	0.039	2.716	35.8	59	70
N18 #2	0.040	0.741	0.030	2.936	46.8	29	47
N18 #3	0.040	0.739	0.030	2.953	47.7	29	47
N20 #1	0.030	0.738	0.022	2.859	43.0	37	51
N20 #2	0.030	0.738	0.022	2.813	40.7	37	51

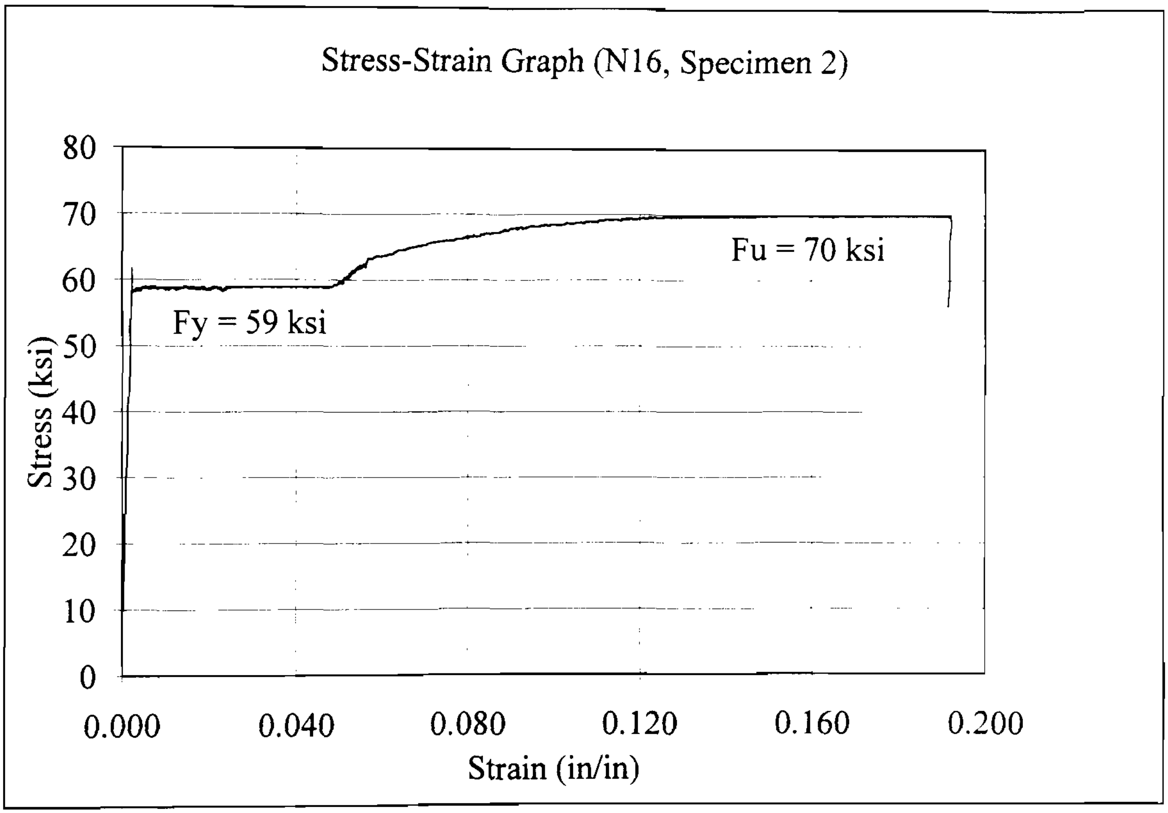


Figure E.1 N16 Stress-Strain Graph (Specimen 2)

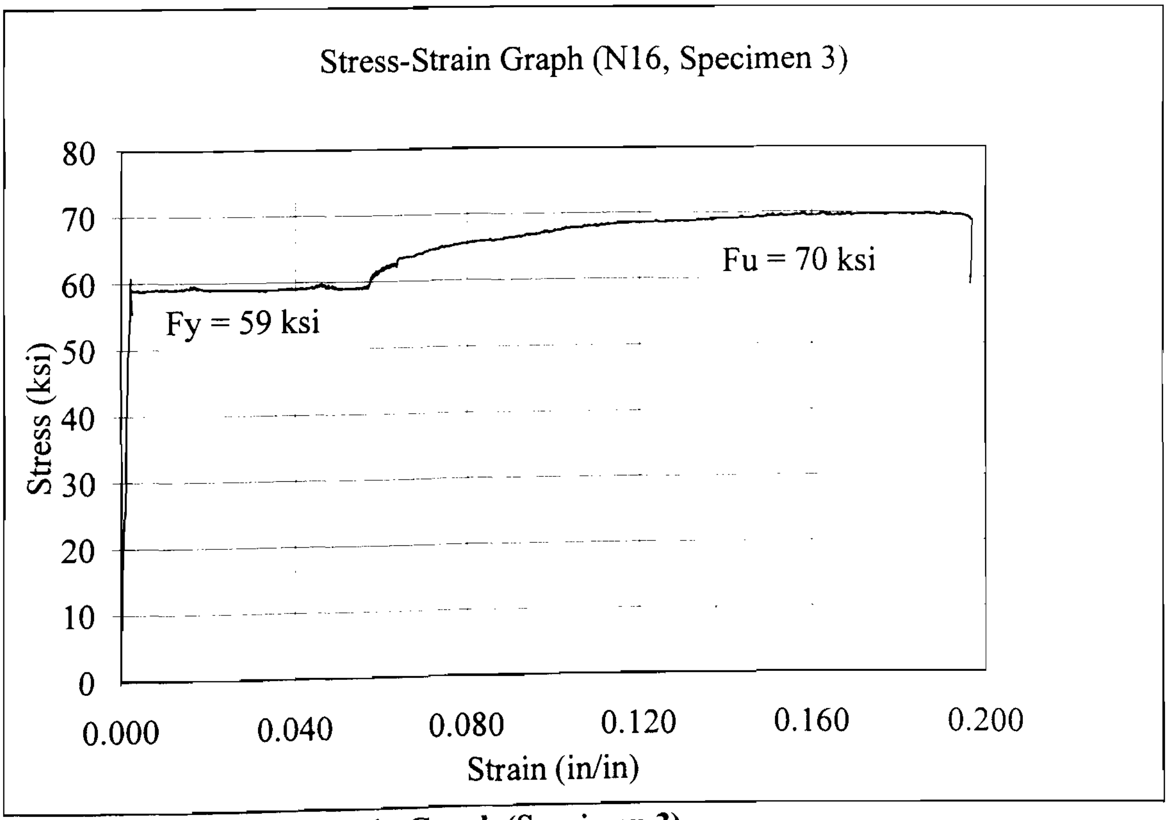


Figure E.2 N16 Stress-Strain Graph (Specimen 3)

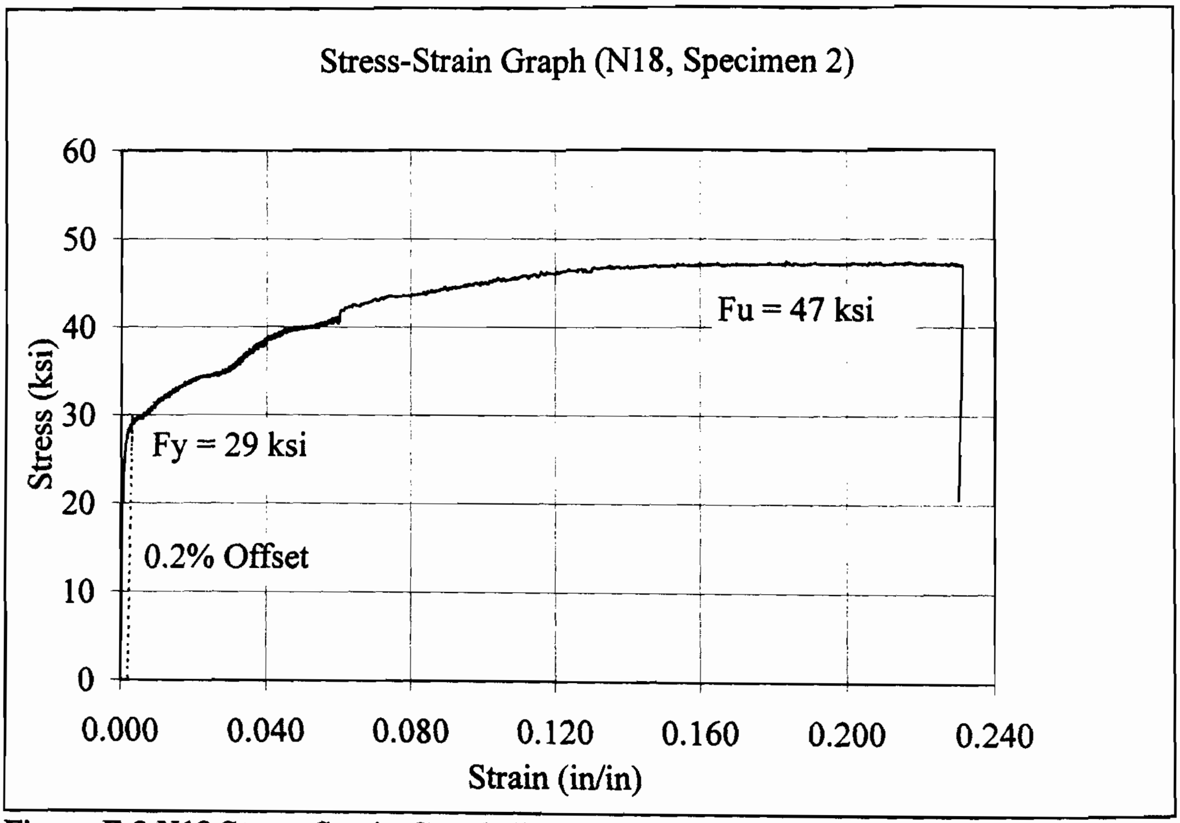


Figure E.3 N18 Stress-Strain Graph (Specimen 2)

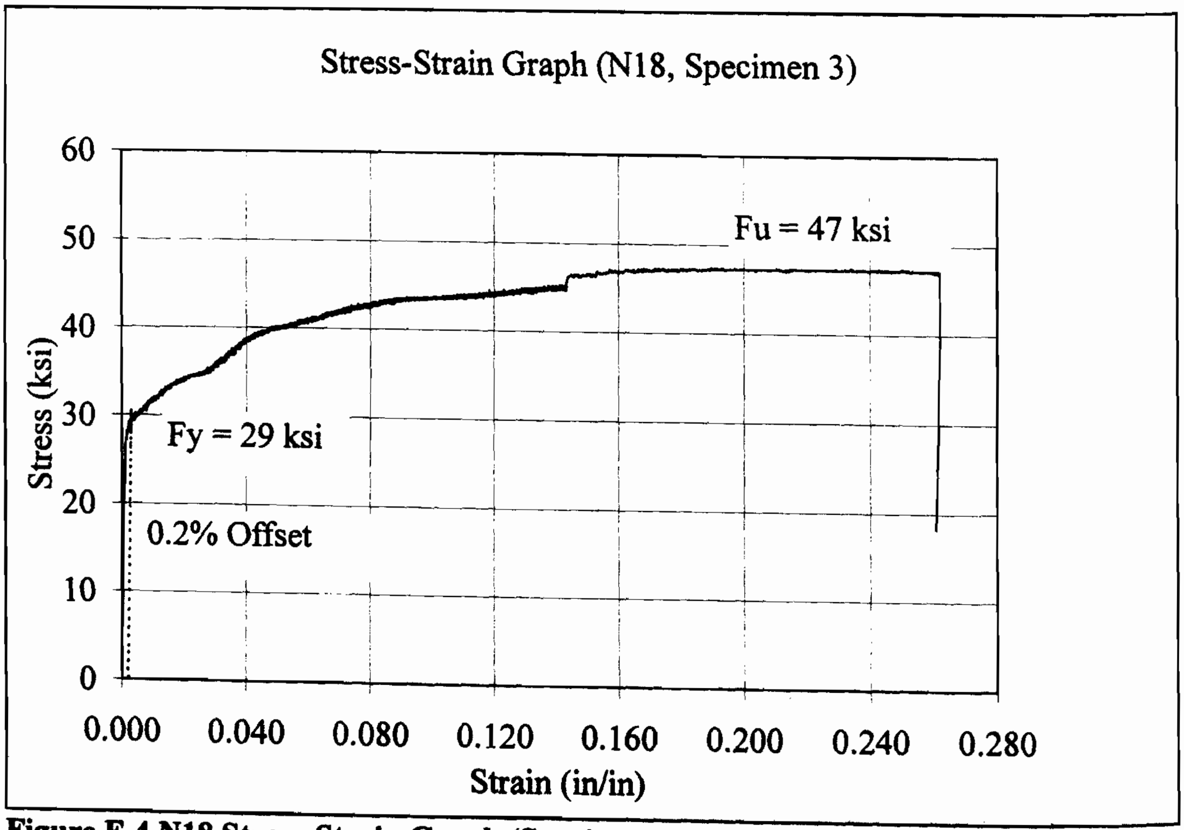


Figure E.4 N18 Stress-Strain Graph (Specimen 3)

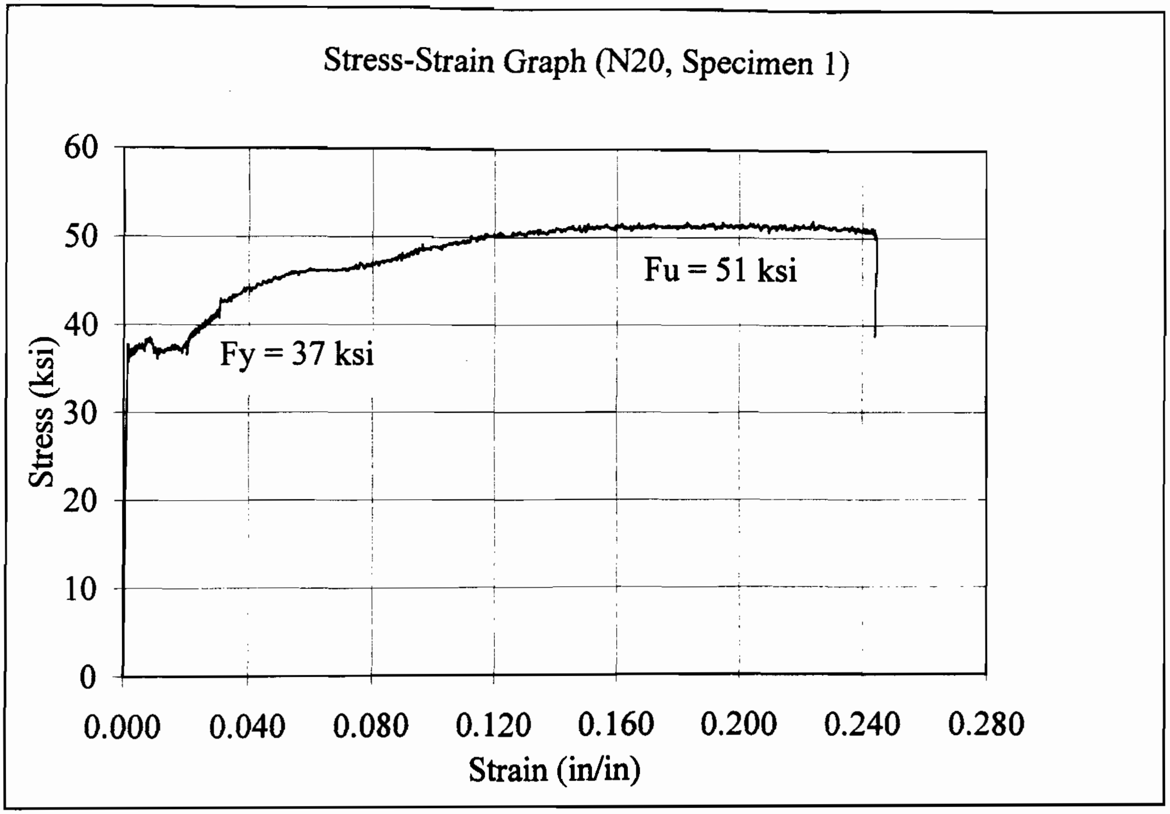


Figure E.5 N20 Stress-Strain Graph (Specimen 1)

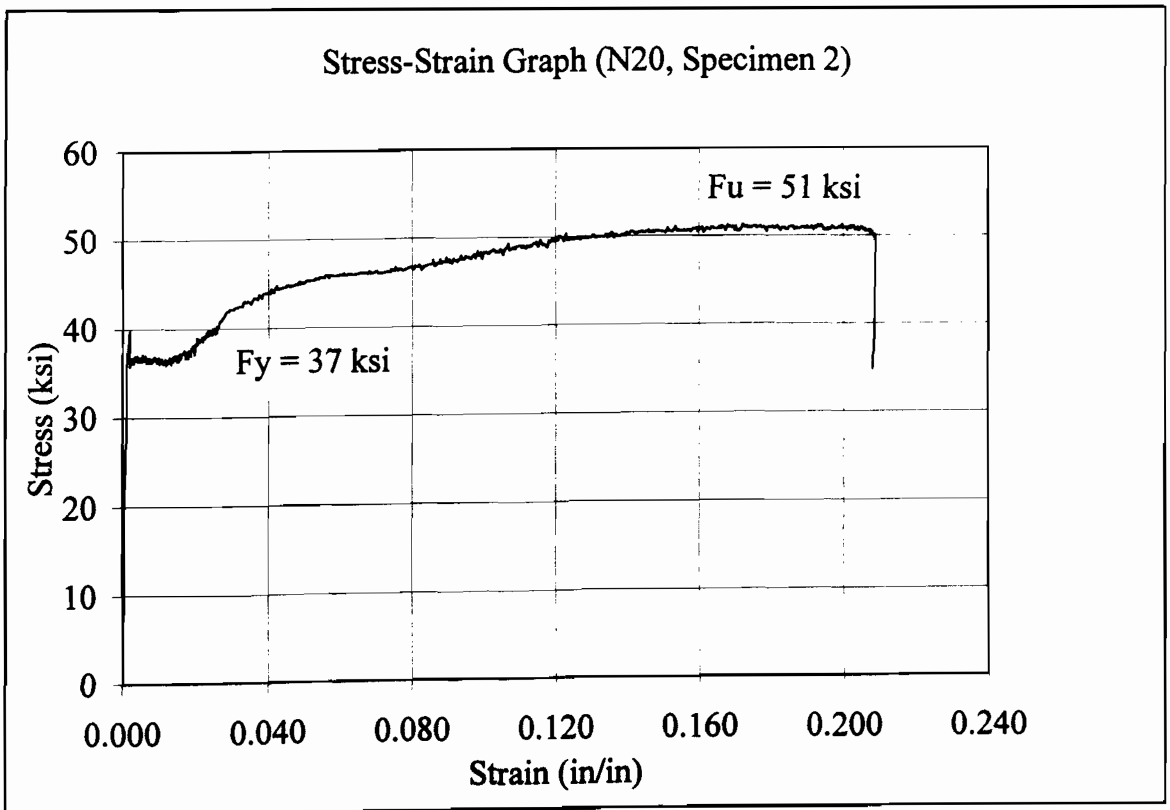


Figure E.6 N20 Stress-Strain Graph (Specimen 2)

APPENDIX F

DATA FOR CONNECTION TESTS

The tables in this section contain all of the data for all of the connection tests. Tests were run with the following parameters varying:

Sheet thickness: N16 (0.053"), N18 (0.040"), and N20 (0.030"). ("N" stands for normal ductility - no low ductility steel was used in this study).

Screw Size: #8, #10, and #12 (for screw dimensions, see Appendix D).

Spacing between screws: 2d or 3d (d being the diameter of the screw threads). These values are rounded - for actual values, see Table F.19.

Pattern: see Figures F.1 through F.12 for patterns; the number in the pattern designation gives the number of screws in the connection.

The topics below explain the headings and terminology used in the data tables:

Pattern: gives the pattern and number of screws in the connection (see Figure F.1).

Test: Test is the unique identifier for a test specimen. An example of a test identifier is N16-3-11. The first three digits indicate the sheet thickness (e.g. N16 indicates normal ductility, 16 gage material). The next digits indicate the bundle number that the specimen came from (in this example, bundle number 3). Sheets came in bundles of about 10. Each identifier indicates the bundle that a specimen originated from (dimensions by bundle are given in Appendix D, "Screw and Sheet Dimensions"). If a bundle number is a single digit (e.g. 3 here), it is a nominal 2" width. If the bundle number is in the 50's (e.g. 53), it is a nominal 3" width. The final digits give the specimen number in a bundle, and are only used to differentiate different specimens.

Strength: This is the strength of the connection, and is the maximum load reached during testing.

Strength per screw: This value is obtained by dividing the strength of the connection by the number of screws in the connection.

Group Effect: Group effect is the strength per screw for a connection divided by the average strength for the single screw connection listed in the table. (For example, to get the group effect value for test N16-1-9 in Table F.1, take 1221 and divide it by the average of 1296 and 1314). The group effect gives an indication of the strength per screw for a connection, compared to the strength for a single screw connection. This is computed because strength equations are currently based on single screw values.

Note: If there is an integer here, the integer refers to the screw number in the connection that is stripped. Figure F.13 shows the numbering scheme for the screws. The main idea is to start with the bottom left screw of the pattern (as shown in Figure F.1) by calling this screw 1. Moving to the right and then up, screws increase in order. "Stripped" is defined as a screw that continues to spin after it has bottomed out against a sheet while being inserted into a connection.

Other notes that occur are the following:

"shim": shims were used to reduce the eccentricity of the connection.

"load ctrl": load control was used (500 lbs/min). Normally stroke control was used (0.1in/min).

"all stripped": all screws in the connection are stripped.

"12D - 7 screws": this specimen was originally fabricated as a 12D pattern, but 7 screws were removed to make it the pattern shown in the table.

"12C - 7 screws": this specimen was originally fabricated as a 12C pattern, but 7 screws were removed to make it the pattern shown in the table.

"frac on head side": usually if fracture occurred between screws, it occurred on the sheet from which the screw threads protruded. Very rarely the opposite occurred, therefore it was noted.

"Grabber screws": screws are listed in Appendix D. Most screws used in connection tests were Dynamic Fastener brand, but a few #12 screws were made by Grabber, and the tests that used Grabber screws are indicated. Dimensions are nearly identical between the two manufacturers.

Failure: All connection failures had some tilting to them. Bearing failures were of interest in this study, therefore they had to be distinguished from fracture failures. The following failure notes are defined:

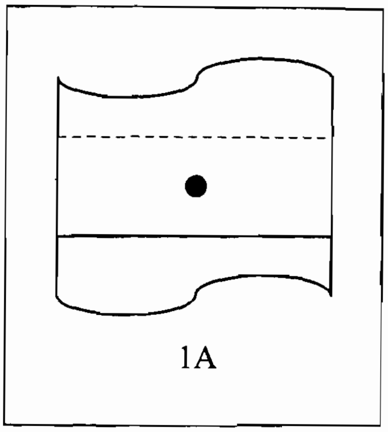
"brg": a bearing failure - gross hole elongation.

"frac": fracture across the net section.

"brg/shear": a combination of bearing failure of the sheet followed by shearing of the screw.

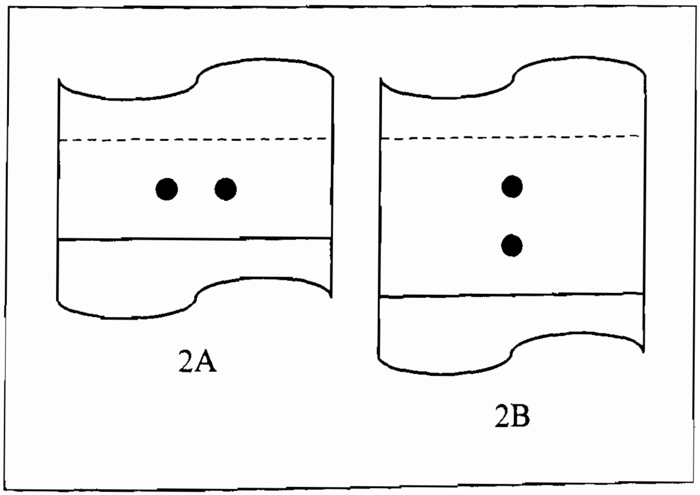
"brg/tear": bearing failure taken until the hole tears out of the sheet.

"brg/frac": bearing failure followed by fracture of the sheet between the screws, followed by complete fracture of the sheet.



1A

Figure F. 1 Screw Pattern for 1 Screw



2A

2B

Figure F. 2 Screw Patterns for 2 Screws

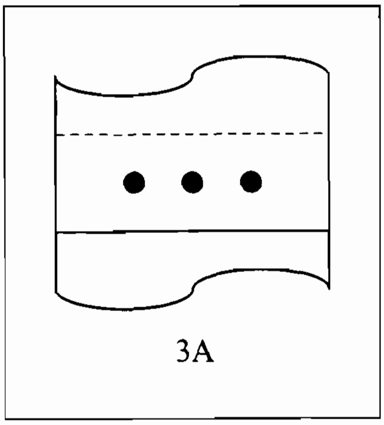


Figure F. 3 Screw Pattern for 3 Screws

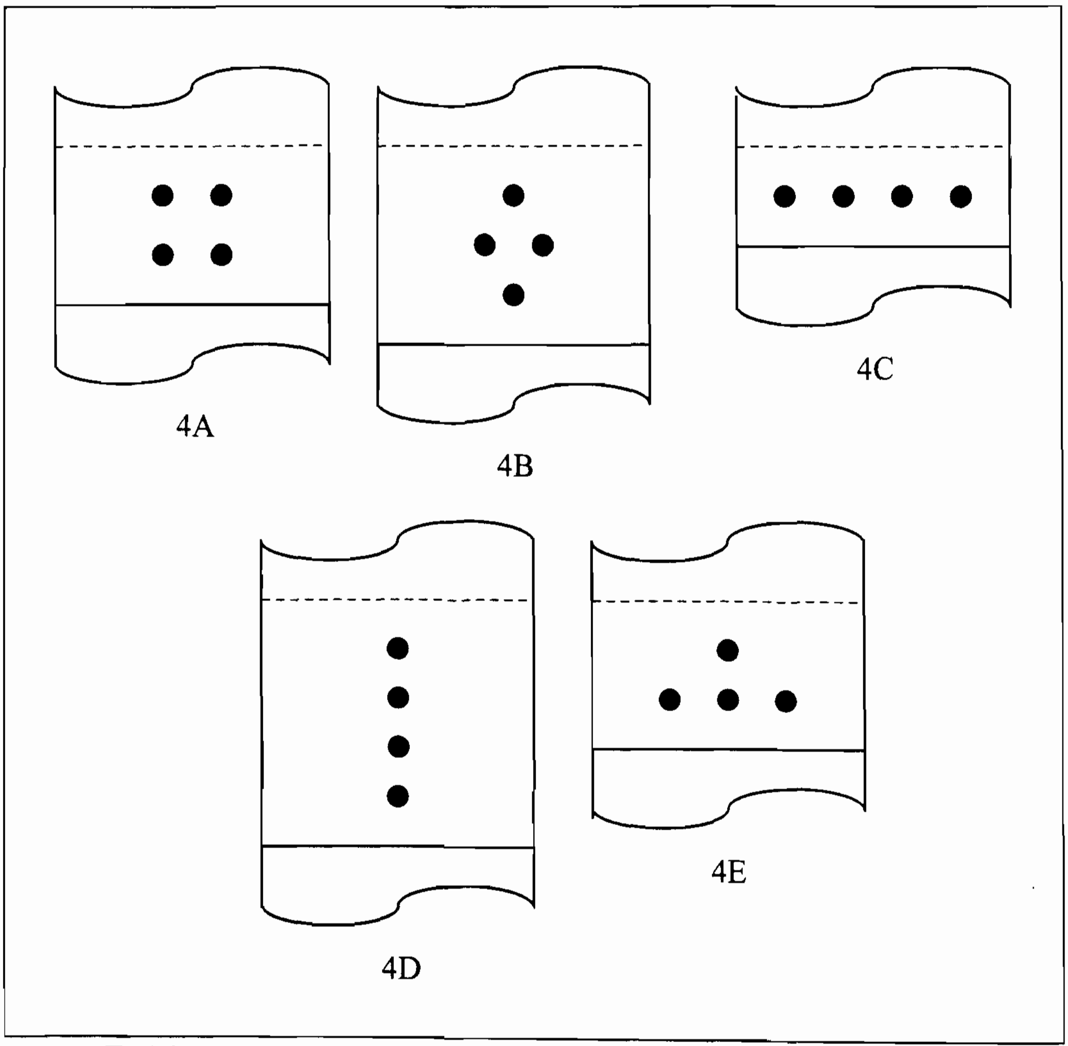


Figure F. 4 Screw Patterns for 4 Screws

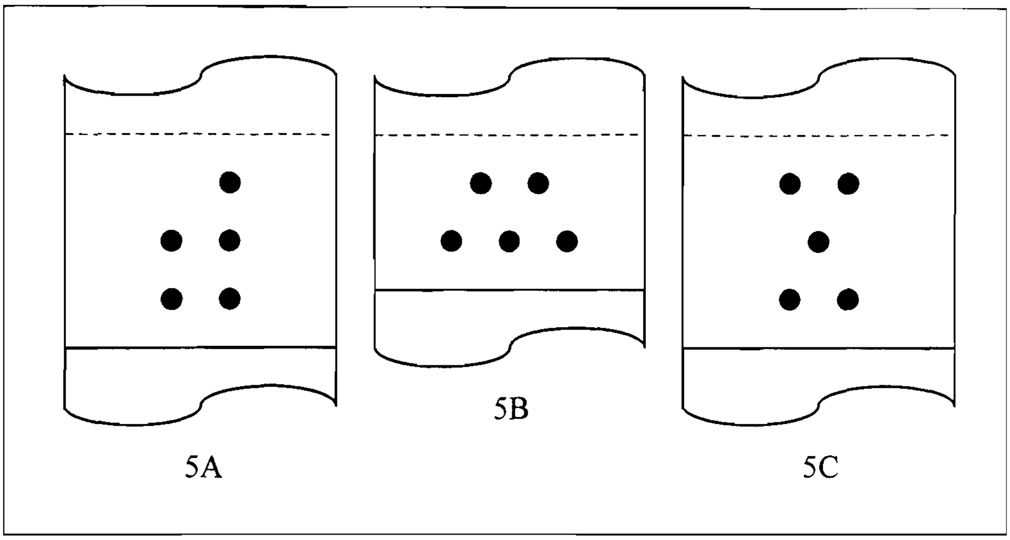


Figure F. 5 Screw Patterns for 5 Screws

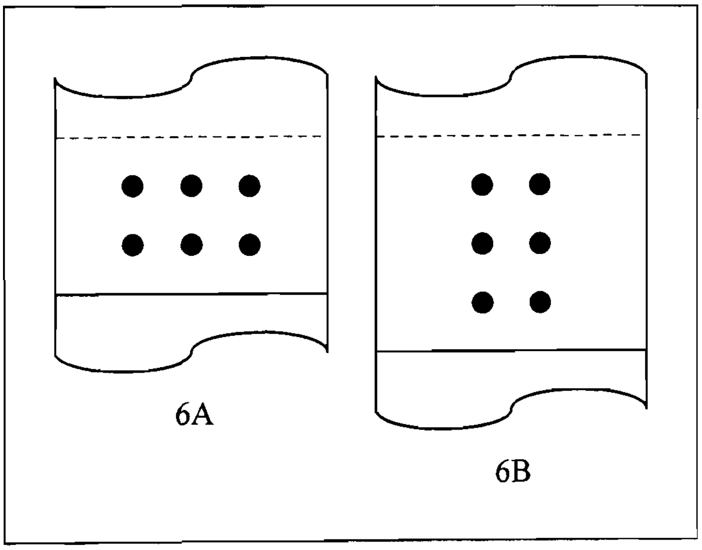


Figure F. 6 Screw Patterns for 6 Screws

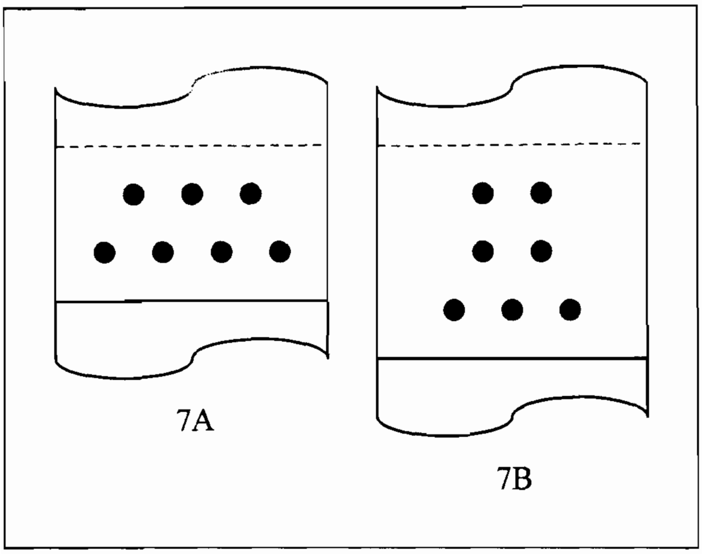


Figure F. 7 Screw Patterns for 7 Screws

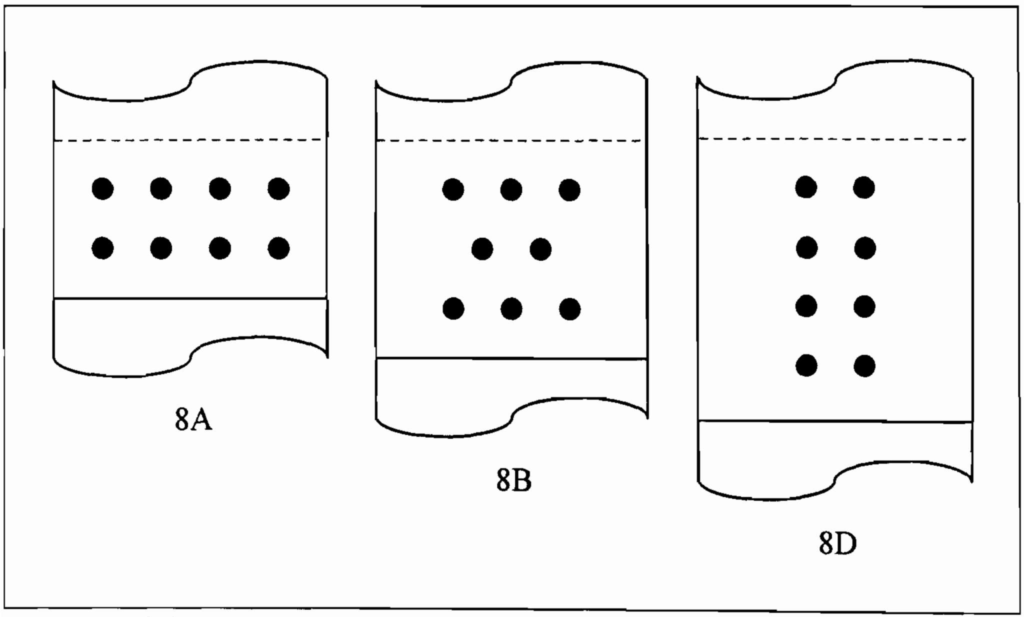
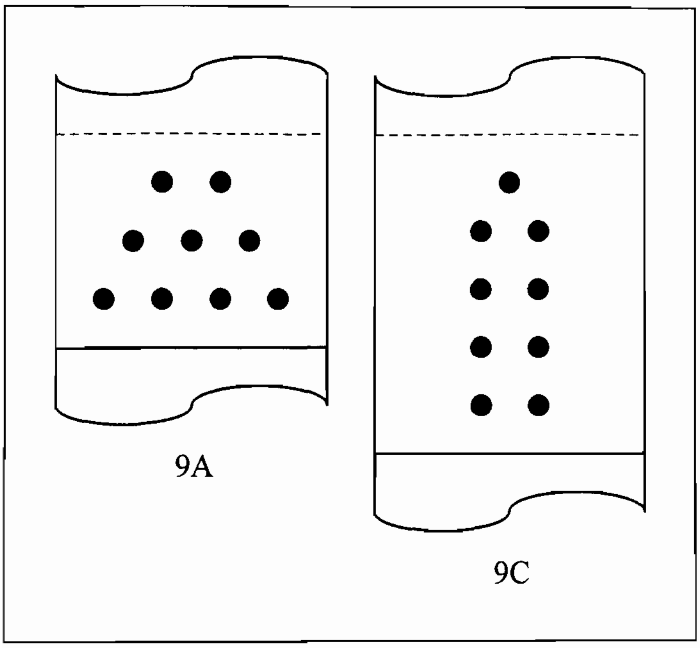


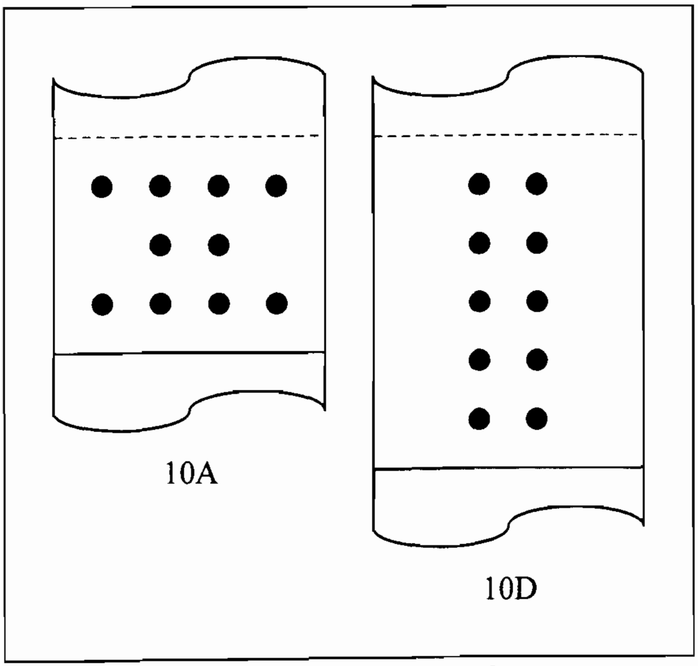
Figure F. 8 Screw Patterns for 8 Screws



9A

9C

Figure F. 9 Screw Patterns for 9 Screws



10A

10D

Figure F. 10 Screw Patterns for 10 Screws

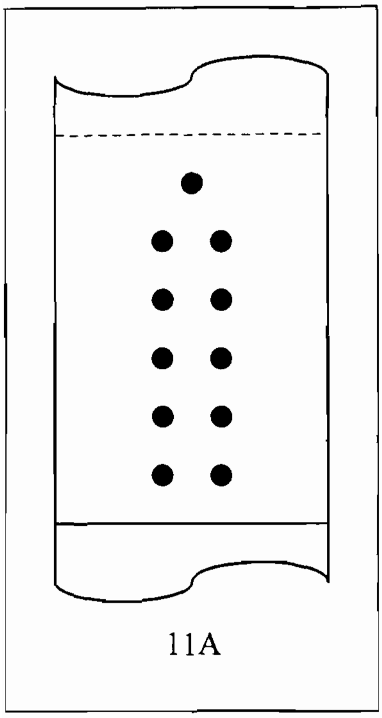


Figure F. 11 Screw Pattern for 11 Screws

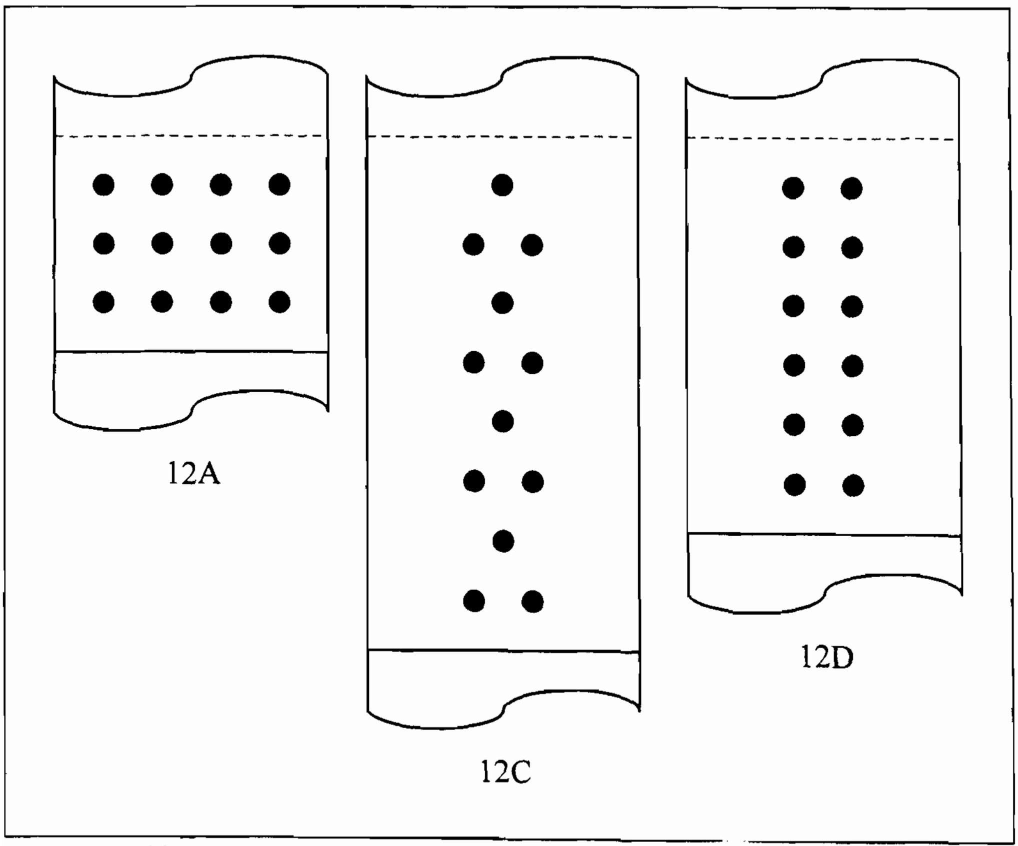


Figure F. 12 Screw Patterns for 12 Screws

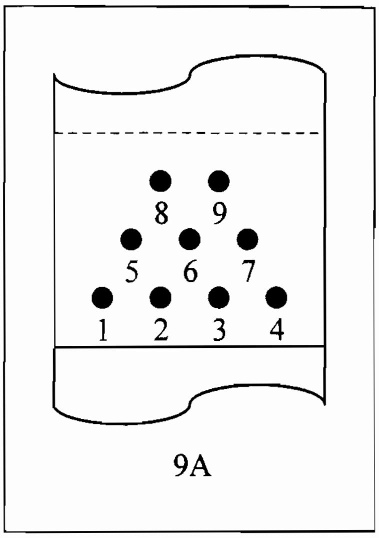


Figure F. 13 Screw Numbering Scheme to Identify Stripped Screws

Table F.1 N16 Sheets, #8 Screw, 3d Spacing

Pattern	**Test**	**Strength (lbs)**	**Strength per screw (lbs)**	**Group Effect**	**Note**	**Failure**
1A	N16-3-11	1296	1296	0.99		brg/shear
1A	N16-50-10	1314	1314	1.01		brg/shear
2A	N16-1-9	2442	1221	0.94		brg/shear
3A	N16-2-1	3315	1105	0.85		brg/shear
4B	N16-2-5	4191	1048	0.80	shim	brg
4B	N16-2-9	4410	1103	0.84		brg
5B	N16-2-2	4839				frac
5B	N16-51-1	5172	1034	0.79		brg
6A	N16-50-9	5910	985	0.75	shim	brg
6A	N16-51-8	6263	1044	0.80		brg
7A	N16-51-2	6597	942	0.72		brg
7A	N16-51-9	6981	997	0.76		brg
8A	N16-50-7	7317	915	0.70		brg
8A	N16-51-5	7473	934	0.72		brg
9A	N16-51-6	7470				frac
9A	N16-52-1	7570				frac
10D	N16-52-2	7913				frac
10D	N16-51-7	7908			3	frac

Table F.2 N18 Sheets, #8 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-1-9	722	722	1.04		brg
1A	N18-52-9	661	661	0.96		brg
2A	N18-1-1	1146	573	0.83		brg
2A	N18-2-4	1197	599	0.87		brg
2B	N18-1-2	1188	594	0.86		brg
2B	N18-2-5	1281	641	0.93		brg
5C	N18-1-3	2555	511	0.74		brg
6A	N18-4-3	2840	473	0.68		brg
6A	N18-2-6	2902	484	0.70		brg
7B	N18-50-1	3347	478	0.69	2	brg
7B	N18-50-7	3350	479	0.69		brg
10A	N18-50-6	4300				frac
10A	N18-50-8	4307			1	frac
11A	N18-50-9	3980				frac

Table F.3 N20 Sheets, #8 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-2-10	519	519	0.99		brg
1A	N20-4-9	534	534	1.01		brg
2A	N20-2-5	749	375	0.71		brg
2A	N20-2-6	789	395	0.75	1	brg
2B	N20-2-7	900	450	0.85	1	brg
2B	N20-2-8	844	422	0.80		brg
4A	N20-3-1	1524	381	0.72		brg
4A	N20-3-2	1506	377	0.72	1	brg
4B	N20-3-3	1563	391	0.74		brg
4B	N20-3-4	1559	390	0.74		brg
4C	N20-50-8	1492	373	0.71		brg
4D	N20-3-6	1663	416	0.79		brg
4E	N20-3-8	1583	396	0.75		brg
6B	N20-3-5	1975	329	0.63		brg
7B	N20-2-9	2353				frac
8A	N20-51-1	2859	357	0.68	4	brg
8A	N20-51-6	2906	363	0.69	7,8	brg
9A	N20-51-5	2896	322	0.61	6,8	brg
9A	N20-51-7	2998	333	0.63	5,9	brg
10A	N20-50-9	3329			3	frac
10D	N20-51-8	3067				frac
11A	N20-51-9	3115				frac

Table F.4 N16 Sheets, #10 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N16-4-11	1534	1534	1.01		brg/shear
1A	N16-2-10	1509	1509	0.99		brg
2A	N16-1-10	2652	1326	0.87		brg/shear
2A	N16-3-1	2697	1349	0.89		brg
2B	N16-3-2	2835	1418	0.93		brg
2B	N16-3-3	2812	1406	0.92		brg
3A	N16-2-3	3596	1199	0.79		brg
4A	N16-2-6	4559	1140	0.75	load ctrl	brg
5B	N16-2-4	5247	1049	0.69		brg
5C	N16-2-7	5321	1064	0.70		brg
7A	N16-50-8	7203	1029	0.68		brg
8B	N16-52-3	7622	953	0.63		brg
8D	N16-52-4	7466	933	0.61		brg
9C	N16-52-5	8094	899	0.59		brg

Table F.5 N18 Sheets, #10 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-52-8	715	715	0.97		brg
1A	N18-4-12	754	754	1.03		brg
2A	N18-1-7	1279	640	0.87		brg
2A	N18-2-7	1158	579	0.79		brg
2B	N18-2-8	1299	650	0.88		brg
2B	N18-2-9	1286	643	0.88	2	brg
4A	N18-1-10	2222	556	0.76		brg
4A	N18-3-1	2310	578	0.79		brg
5B	N18-1-8	2600	520	0.71		brg
5C	N18-2-1	2743	549	0.75		brg
8A	N18-50-3	4114	514	0.70		brg
8D	N18-50-10	3790				frac
9C	N18-51-1	4029				frac

Table F.6 N20 Sheets, #10 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-3-10	507	507	0.98		brg
1A	N20-54-1	524	524	1.02		brg
2A	N20-3-9	786	393	0.76	1	brg
2A	N20-4-4	952	476	0.92		brg
2B	N20-4-5	930	465	0.90		brg
2B	N20-4-6	1005	503	0.97		brg
4A	N20-4-2	1601	400	0.78		brg
4A	N20-4-7	1615	404	0.78		brg
5C	N20-4-3	1972	394	0.77	5	brg
5C	N20-4-8	2043	409	0.79		brg
6A	N20-4-1	2248	375	0.73	1,4,6	brg
10A	N20-51-3	3444			all stripped	frac
10A	N20-51-4	3528				frac
11A	N20-52-1	3337				frac

Table F.7 N16 Sheets, #12 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N16-4-9	1561	1561	0.96		brg
1A	N16-1-11	1677	1677	1.04		brg
2A	N16-1-4	2939	1470	0.91		brg
2A	N16-3-4	2998	1499	0.93		brg
2B	N16-1-1	2946	1473	0.91		brg
2B	N16-1-2	2968	1484	0.92		brg
4A	N16-1-5	4890	1223	0.76		brg
4A	N16-1-6	4868	1217	0.75		brg
4B	N16-1-7	5064	1266	0.78		brg
4B	N16-1-8	5120	1280	0.79		brg
6A	N16-50-5	7179	1197	0.74		brg
6A	N16-50-6	7095	1183	0.73		brg
7A	N16-50-3	7896				frac
7A	N16-50-4	8084				frac
8A	N16-50-1	8586				frac
8A	N16-50-2	8462				frac
8D	N16-52-6	8257	1032	0.64		brg

Table F.8 N18 Sheets, #12 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-52-7	811	811	1.03		brg
1A	N18-3-10	759	759	0.97		brg
2A	N18-1-4	1445	723	0.92		brg
2A	N18-3-2	1246	623	0.79		brg
2B	N18-1-5	1388	694	0.88		brg
2B	N18-3-3	1450	725	0.92		brg
4B	N18-3-4	2570	643	0.82		brg
4B	N18-3-5	2533	633	0.81		brg
5C	N18-3-6	3021	604	0.77		brg
5C	N18-3-7	3040	608	0.77		brg
7B	N18-50-4	4030	576	0.73		brg
7B	N18-51-2	4032	576	0.73		brg
8A	N18-50-5	4668	584	0.74		brg
8A	N18-51-3	4734	592	0.75		brg
8D	N18-51-4	4205	526	0.67		brg

Table F.9 N20 Sheets, #12 Screw, 3d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-5-12	591	591	1.00		brg
1A	N20-1-11	590	590	1.00		brg
2A	N20-1-7	965	483	0.82	1, Grabber screws	brg
2A	N20-1-8	864	432	0.73	Grabber screws	brg
2B	N20-1-9	1012	506	0.86	Grabber screws	brg
2B	N20-1-10	1010	505	0.86	Grabber screws	brg
4A	N20-1-1	1762	441	0.75	Grabber screws	brg
4A	N20-1-2	1860	465	0.79	Grabber screws	brg
4B	N20-1-3	1737	434	0.74	Grabber screws	brg
4B	N20-1-4	1737	434	0.74	Grabber screws	brg
5A	N20-2-1	2197	439	0.74	12D - 7 screws Grabber screws	brg
5A	N20-2-2	2142	428	0.73	12D - 7 screws, 4 Grabber screws	brg
5C	N20-2-4	2489	498	0.84	12C - 7 screws Grabber screws	brg
6A	N20-50-6	2739	457	0.77		brg
6A	N20-50-7	2610	435	0.74		brg
6B	N20-1-5	2573	429	0.73	Grabber screws	brg
6B	N20-1-6	2530	422	0.71	Grabber screws	brg
7A	N20-50-4	3360	480	0.81		brg
7A	N20-50-5	3329	476	0.81		brg
8A	N20-50-2	3570	446	0.76		brg
8A	N20-50-3	3656	457	0.77		brg
8D	N20-52-2	3272	409	0.69		brg
12A	N20-50-1	3768			7, Grabber screws	frac
12C	N20-2-3	2686			12, Grabber screws	frac

Table F.10 N16 Sheets, #8 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N16-3-11	1296	1296	0.99		brg/shear
1A	N16-50-10	1314	1314	1.01		brg/shear
2A	N16-3-6	2348	1174	0.90		brg/shear
2A	N16-3-7	2274	1137	0.87		brg/shear
4A	N16-3-8	3841	960	0.74		brg/frac
4A	N16-3-9	3679	920	0.70		brg/frac
6A	N16-52-7	5288	881	0.68		brg/frac
6A	N16-52-8	5239	873	0.67		brg/frac
8A	N16-52-9	6034	754	0.58		brg/frac
8A	N16-53-1	5959	745	0.57		brg/frac

Table F.11 N18 Sheets, #8 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-1-9	722	722	1.04		brg
1A	N18-52-9	661	661	0.96		brg
2A	N18-3-8	1230	615	0.89		brg/tear
2A	N18-4-1	1146	573	0.83		brg/tear
4A	N18-3-9	1934	484	0.70		brg/frac
4A	N18-4-2	1865	466	0.67		brg/frac
6A	N18-51-5	2585	431	0.62		brg/frac
6A	N18-51-6	2543	424	0.61		brg/frac
8A	N18-51-7	3181	398	0.58		brg/frac
8A	N18-51-8	3085	386	0.56		brg/frac

Table F.12 N20 Sheets, #8 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-2-10	519	519	0.99		brg
1A	N20-4-9	534	534	1.01		brg
2A	N20-5-4	791	396	0.75		brg/tear
2A	N20-52-3	819	410	0.78	1	brg/tear
4A	N20-5-5	1402	351	0.67	2	brg/frac
4A	N20-52-4	1442	361	0.68	2	brg/frac
6A	N20-52-5	1883	314	0.60		brg/frac
6A	N20-52-6	1910	318	0.60		brg/frac
8A	N20-52-7	2442	305	0.58		brg/frac
8A	N20-52-8	2313	289	0.55		brg/frac

Table F.13 N16 Sheets, #10 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N16-4-11	1534	1534	1.01		brg/shear
1A	N16-2-10	1509	1509	0.99		brg
2A	N16-3-10	2469	1235	0.81		brg/tear
2A	N16-4-1	2615	1308	0.86		brg/tear
4A	N16-4-2	3809	952	0.63		brg/frac
4A	N16-4-3	3894	974	0.64		brg/frac
6A	N16-53-2	5244	874	0.57		brg/frac
6A	N16-53-3	5106	851	0.56		brg/frac
8A	N16-53-4	6157	770	0.51		brg/frac
8A	N16-53-5	5741	718	0.47		brg/frac

Table F.14 N18 Sheets, #10 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-52-8	715	715	0.97		brg
1A	N18-4-12	754	754	1.03		brg
2A	N18-4-8	1212	606	0.83		brg/tear
2A	N18-4-9	1252	626	0.85		brg/tear
4A	N18-4-10	1817	454	0.62		brg/frac
4A	N18-4-11	2038	510	0.69		brg/frac
6A	N18-52-3	2582	430	0.59		brg/frac
6A	N18-52-4	2577	430	0.58		brg/frac
8A	N18-52-5	3174	397	0.54		brg/frac
8A	N18-52-6	3169	396	0.54		brg/frac

Table F.15 N20 Sheets, #10 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-3-10	507	507	0.98		brg
1A	N20-54-1	524	524	1.02		brg
2A	N20-5-6	861	431	0.84		brg/tear
2A	N20-53-4	859	430	0.83		brg/tear
4A	N20-5-7	1397	349	0.68		brg/frac
4A	N20-53-5	1432	358	0.69		brg/frac
6A	N20-52-9	2044	341	0.66		brg/frac
6A	N20-53-1	1956	326	0.63		brg/frac
8A	N20-53-2	2320	290	0.56		brg/frac
8A	N20-53-3	2412	302	0.58		brg/frac

Table F.16 N16 Sheets, #12 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N16-4-9	1561	1561	0.96		brg
1A	N16-1-11	1677	1677	1.04		brg
2A	N16-4-8	2718	1359	0.84		brg/tear
2A	N16-4-5	2993	1497	0.92		brg/tear
4A	N16-4-6	4039	1010	0.62		brg/frac
4A	N16-4-7	4227	1057	0.65		brg/frac
6A	N16-53-6	5586	931	0.58		brg/frac
6A	N16-53-7	5726	954	0.59	frac on head side	brg/frac
8A	N16-53-8	6437	805	0.50		brg/frac
8A	N16-53-9	6464	808	0.50		brg/frac

Table F.17 N18 Sheets, #12 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N18-52-7	811	811	1.03		brg
1A	N18-3-10	759	759	0.97		brg
2A	N18-4-4	1501	751	0.96		brg/tear
2A	N18-4-5	1371	686	0.87		brg/tear
4A	N18-4-6	2048	512	0.65		brg/frac
4A	N18-4-7	1976	494	0.63		brg/frac
6A	N18-51-9	2892	482	0.61		brg/frac
6A	N18-52-1	2770	462	0.59		brg/frac
8A	N18-51-10	3322	415	0.53		brg/frac
8A	N18-52-2	3345	418	0.53		brg/frac

Table F.18 N20 Sheets, #12 Screw, 2d Spacing

Pattern	Test	Strength (lbs)	Strength per screw (lbs)	Group Effect	Note	Failure
1A	N20-5-12	591	591	1.00		brg
1A	N20-1-11	590	590	1.00		brg
2A	N20-5-8	977	489	0.83		brg/tear
2A	N20-5-9	1022	511	0.87		brg/tear
4A	N20-5-10	1452	363	0.61	frac on head side	brg/frac
4A	N20-5-11	1573	393	0.67		brg/frac
6A	N20-53-6	2316	386	0.65	frac on head side	brg/frac
6A	N20-53-7	2310	385	0.65	frac on head side	brg/frac
8A	N20-53-8	2667	333	0.56		brg/frac
8A	N20-53-9	2672	334	0.57		brg/frac

Explanation of Table F.19:

For each of the three screw sizes used in connection tests, edge distances and screw spacings were described in terms of d, the screw thread outer diameter. The American Iron and Steel Institute Cold-Formed Steel Design Specification sets as minimums 1.5d for transverse edge distance, and 3d for longitudinal edge distance and screw spacing. Transverse edge distance was kept at a minimum of 1.5d (usually transverse edge distance greatly exceeded this). Longitudinal edge distance was kept at 3d, and screw spacing was either 2d or 3d. When these quantities were calculated, the amount would be rounded up to the nearest 1/16” for practicality in marking sheets and placing screws, as well as to create a reasonable tolerance for screw placement. Due to this round up, longitudinal edge distance and screw spacing slightly exceed 2d and 3d, which is the purpose of Table F.19. The headings are described below:

“Screw”: screw size.

“d (in)”: outer diameter of screw threads.

“1.5d actual”: actual 1.5d.

“1.5d used”: the value of 1.5d that was adhered to.

“2d actual”: actual 2d.

“2d used”: the value of 2d that was adhered to.

“2d Ratio”: actual ratio of adhered 2d to d.

“3d actual”: actual 3d.

“3d used”: the value of 3d that was adhered to.

“3d Ratio”: actual ratio of adhered 3d to d.

Table F.19 Screw Spacing and Edge Distances

Screw	d (in)	1.5d actual	1.5d used	2d actual	2d used	2d Ratio	3d actual	3d used	3d Ratio
#8	0.165	0.248	1/4	0.331	3/8	2.27	0.496	1/2	3.03
#10	0.186	0.279	5/16	0.372	3/8	2.02	0.558	9/16	3.02
#12	0.215	0.323	3/8	0.431	7/16	2.03	0.646	11/16	3.20

APPENDIX G

EQUATIONS FOR CONNECTION TESTS

Equation (G-1) is the general form used for best fit lines in the Connection Graphs of Appendices H, I, and J. The values of the constants are given in table G.1.

$$S = an + b \tag{G-1}$$

where:

S = connection strength (lbs)

a = constant (lbs/screw) = slope of line in graph

n = number of screws in connection

b = constant (lbs) = y-intercept on graph (at 0 screws)

Equation (G-2) is the general form used for best fit lines in the Group Effect Graphs of Appendices K, L, and M. The values of the constants are given in table G.2.

$$R = c + \frac{d}{\sqrt{n}} \tag{G-2}$$

where:

R = group effect (ratio of connection strength per screw to strength of single screw connection)

c = constant

n = number of screws in connection

d = constant

Table G.1 Constants for Best Fit Connection Equations

Sheet Thickness (gage)	Screw Size (#)	Screw Spacing	a	b	r^2
16	8	3d	877	639	0.991
18	8	3d	434	308	0.997
20	8	3d	315	239	0.987
16	10	3d	828	1021	0.990
18	10	3d	482	286	0.997
20	10	3d	355	193	0.990
16	12	3d	991	922	0.986
18	12	3d	531	324	0.992
20	12	3d	430	105	0.983
16	8	2d	678	878	0.980
18	8	2d	345	446	0.992
20	8	2d	265	290	0.995
16	10	2d	631	1159	0.986
18	10	2d	343	489	0.991
20	10	2d	267	309	0.990
16	12	2d	683	1274	0.976
18	12	2d	356	583	0.982
20	12	2d	302	347	0.985

Table G.2 Constants for Best Fit Group Effect Equations

Sheet Thickness (gage)	Screw Size (#)	Screw Spacing	c	d	r^2
16	8	3d	0.588	0.432	0.926
18	8	3d	0.496	0.516	0.935
20	8	3d	0.478	0.486	0.832
16	10	3d	0.425	0.620	0.939
18	10	3d	0.530	0.466	0.917
20	10	3d	0.574	0.433	0.758
16	12	3d	0.515	0.521	0.904
18	12	3d	0.577	0.427	0.873
20	12	3d	0.609	0.344	0.656
16	8	2d	0.397	0.630	0.950
18	8	2d	0.345	0.676	0.963
20	8	2d	0.332	0.655	0.984
16	10	2d	0.239	0.785	0.976
18	10	2d	0.294	0.724	0.974
20	10	2d	0.364	0.646	0.984
16	12	2d	0.256	0.781	0.938
18	12	2d	0.287	0.758	0.915
20	12	2d	0.344	0.668	0.959

APPENDIX H

CONNECTION GRAPHS - 3D VS. 2D SPACING

The purpose of this appendix is to show the effect of 2d versus 3d spacing. In all cases, 2d spacing gives lower capacity for the same sheet thickness and number of screws. See Appendix G for best fit equations.

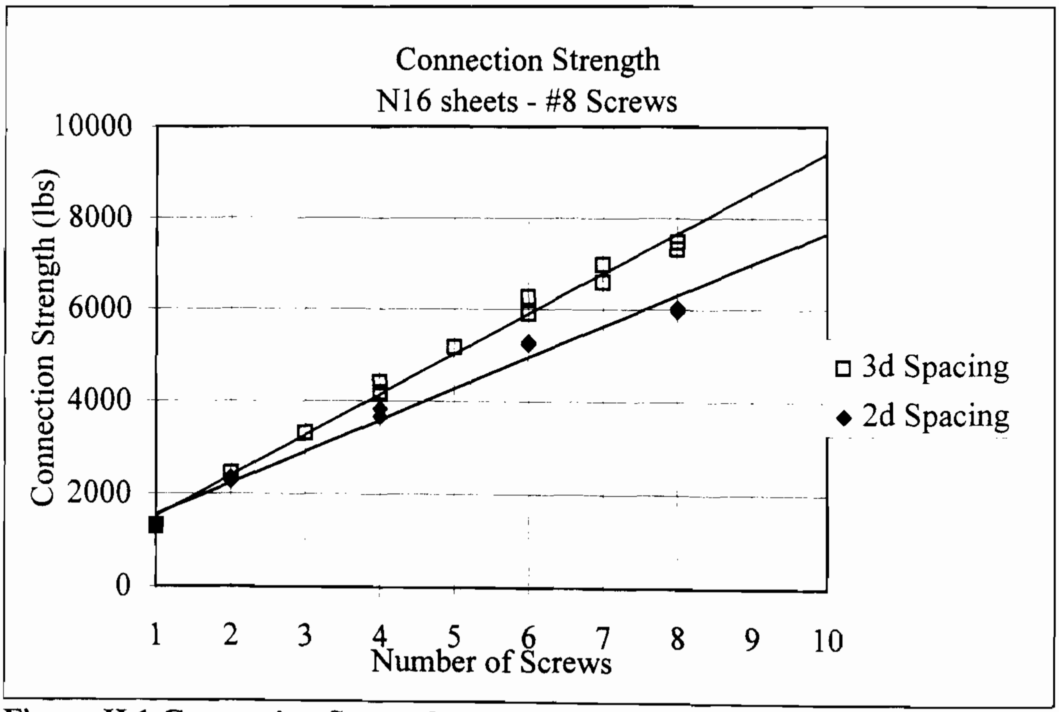


Figure H.1 Connection Strength - N16 Sheets - #8 Screws - 3d vs. 2d Spacing

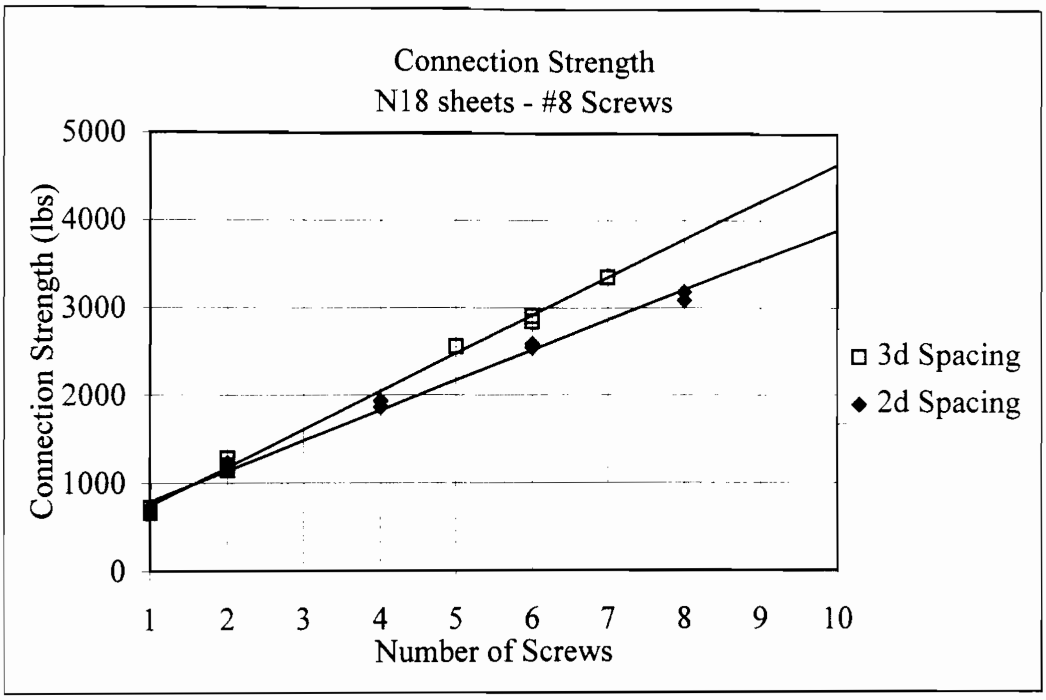


Figure H.2 Connection Strength - N18 Sheets - #8 Screws - 3d vs. 2d Spacing

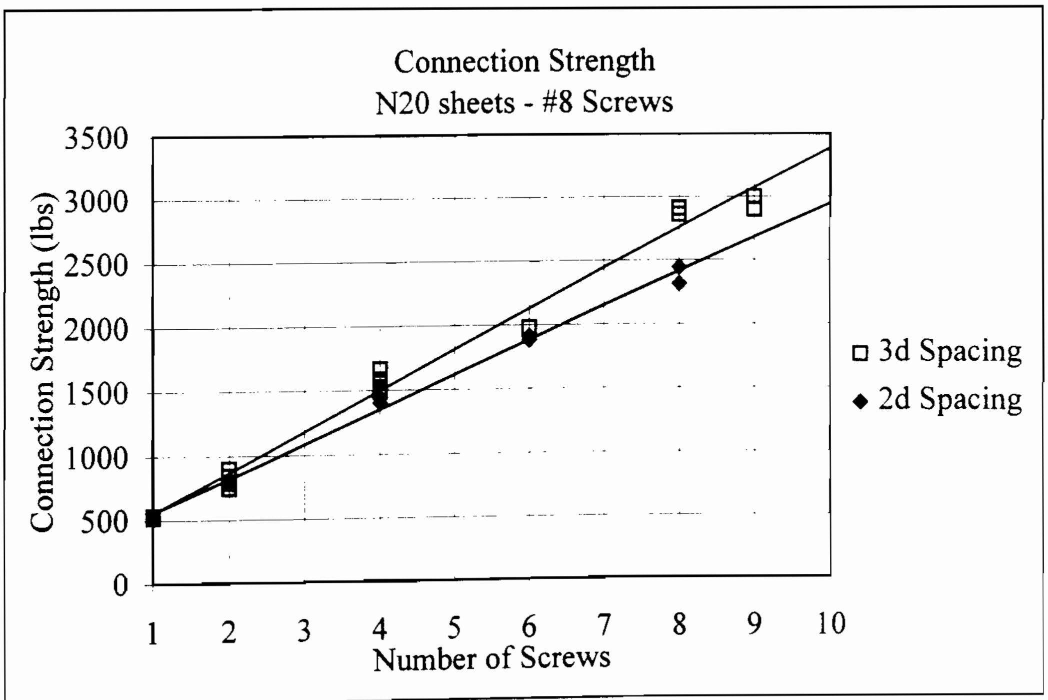


Figure H.3 Connection Strength - N20 Sheets - #8 Screws - 3d vs. 2d Spacing

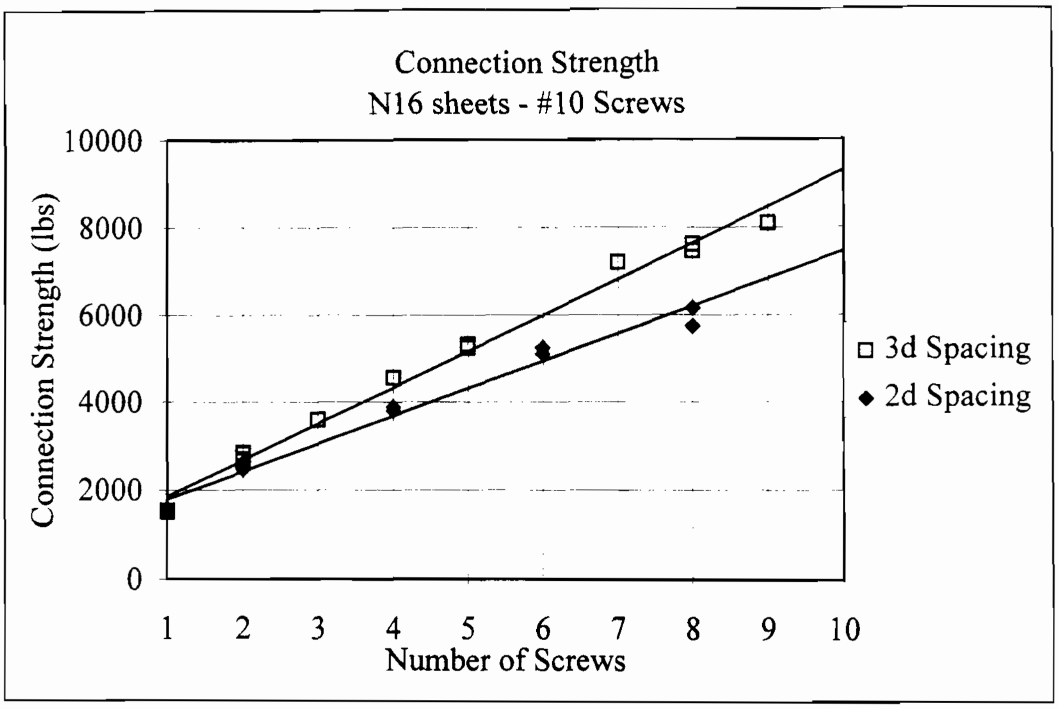


Figure H.4 Connection Strength - N16 Sheets - #10 Screws - 3d vs. 2d Spacing

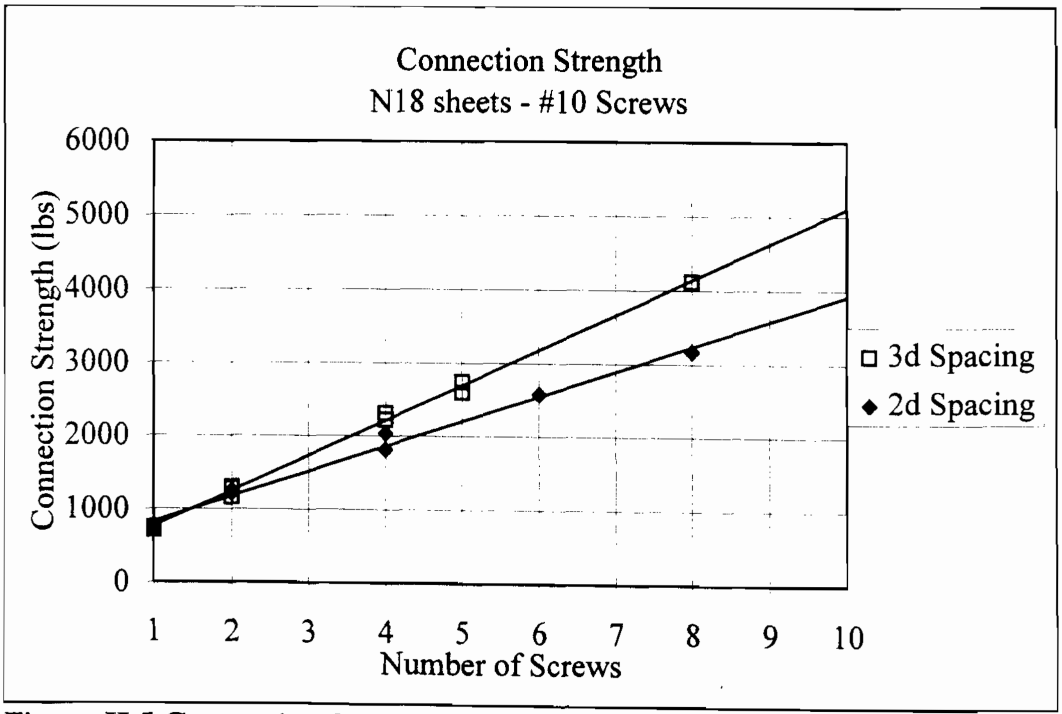


Figure H.5 Connection Strength - N18 Sheets - #10 Screws - 3d vs. 2d Spacing

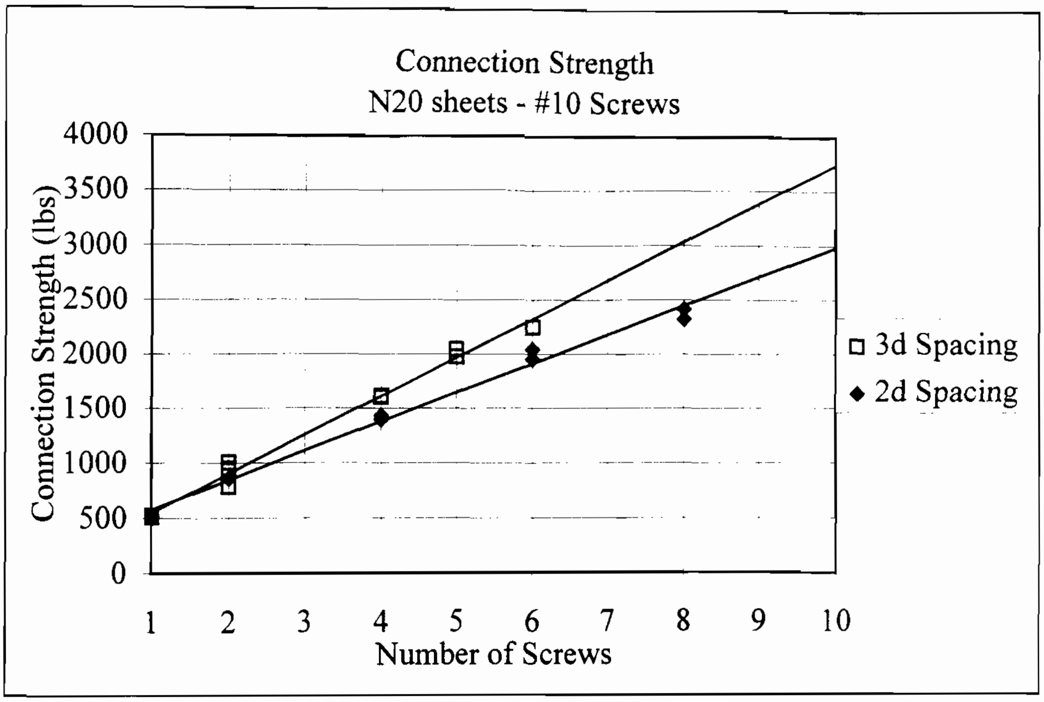


Figure H.6 Connection Strength - N20 Sheets - #10 Screws - 3d vs. 2d Spacing

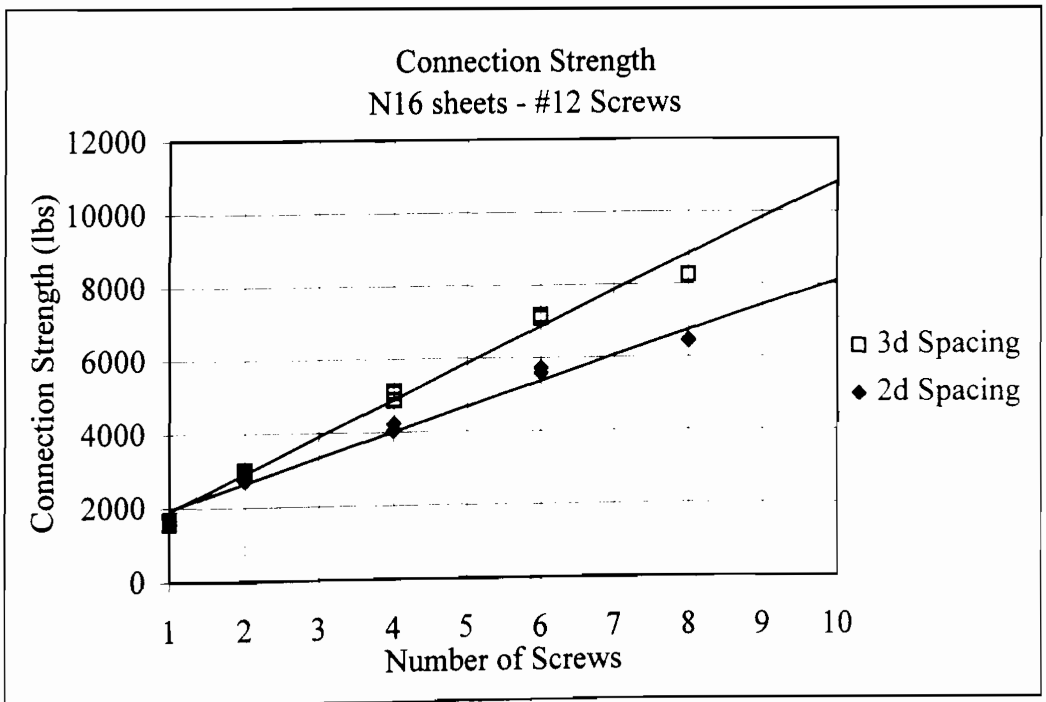


Figure H.7 Connection Strength - N16 Sheets - #12 Screws - 3d vs. 2d Spacing

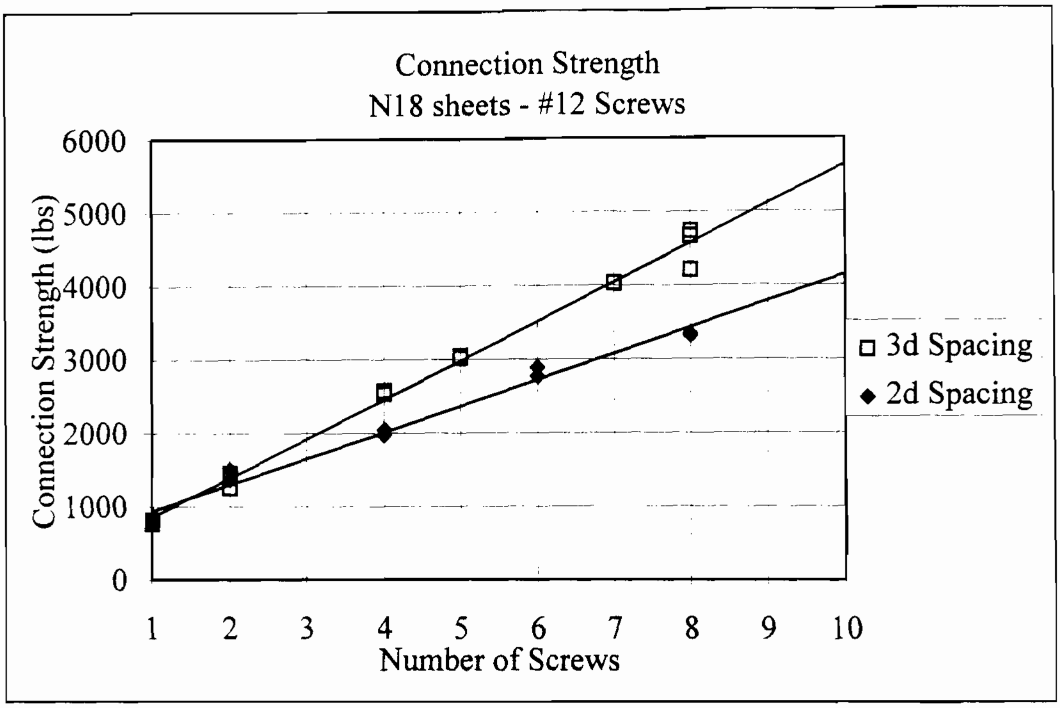


Figure H.8 Connection Strength - N18 Sheets - #12 Screws - 3d vs. 2d Spacing

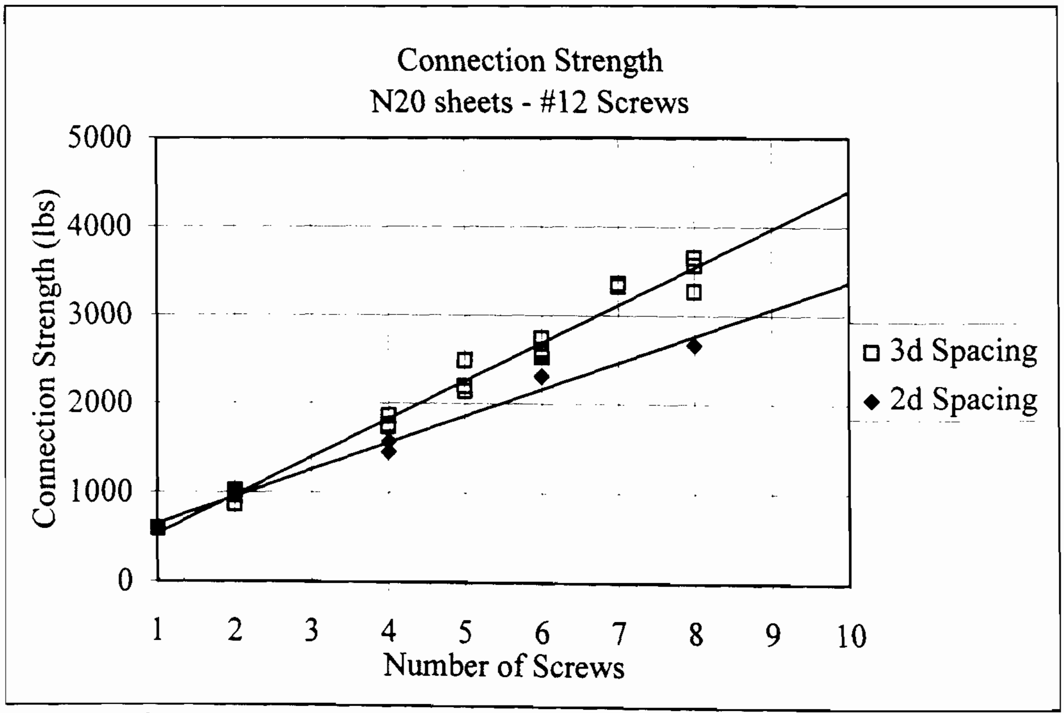


Figure H.9 Connection Strength - N20 Sheets - #12 Screws - 3d vs. 2d Spacing

APPENDIX I

CONNECTION GRAPHS - BY SHEET THICKNESS

The purpose of this appendix is to demonstrate that screw size has little impact on the connection strength. In the graphs below, the sheet size and screw spacing remain constant for each graph, only the screw size varies. See Appendix G for best fit equations.

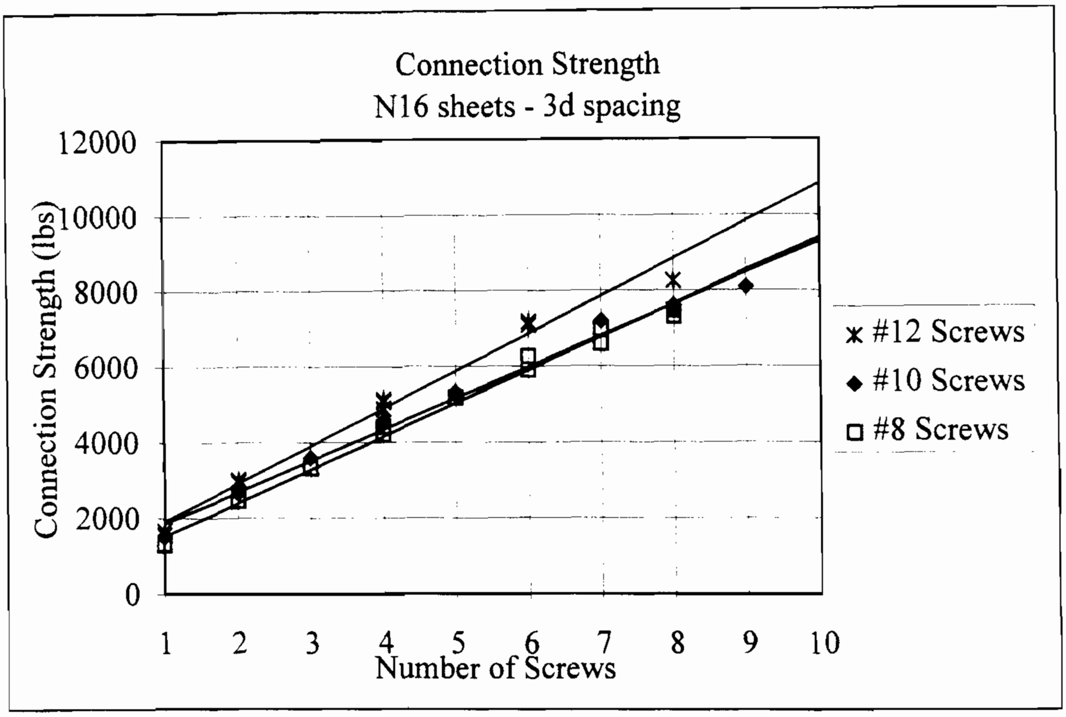


Figure I.1 Connection Strength - N16 Sheets - 3d Spacing - Screws vary

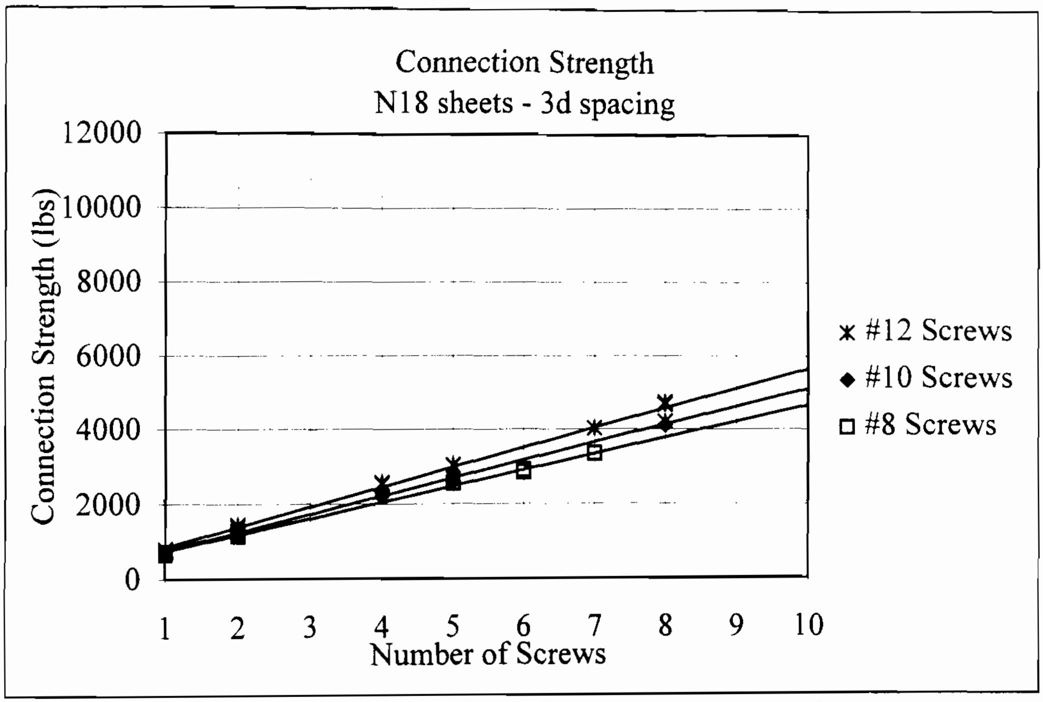


Figure I.2 Connection Strength - N18 Sheets - 3d Spacing - Screws vary

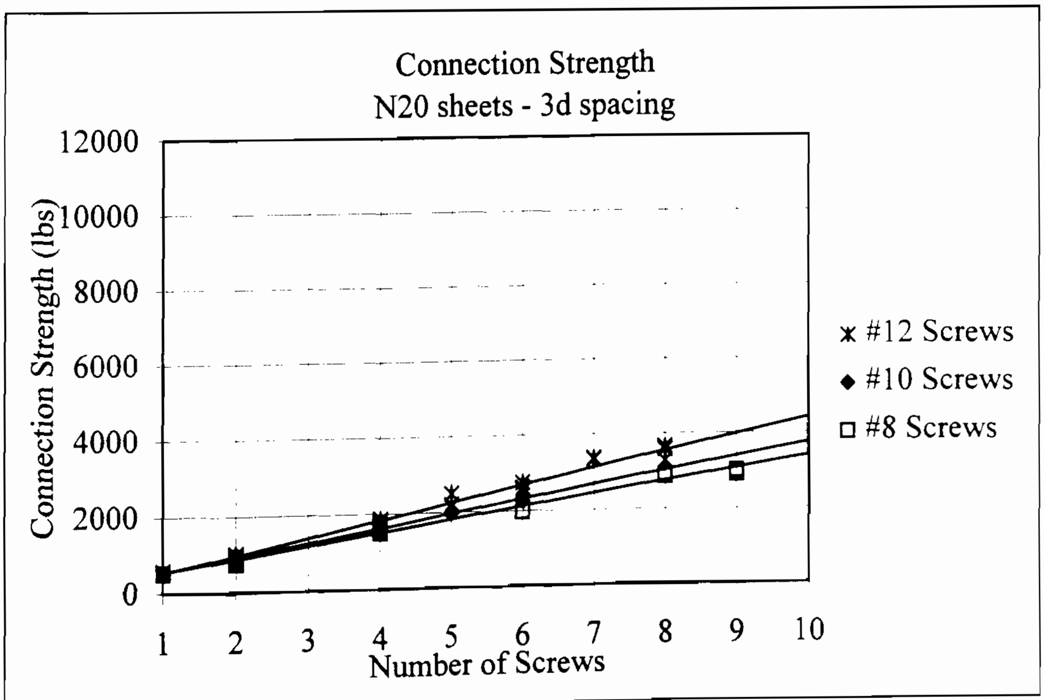


Figure I.3 Connection Strength - N20 Sheets - 3d Spacing - Screws vary

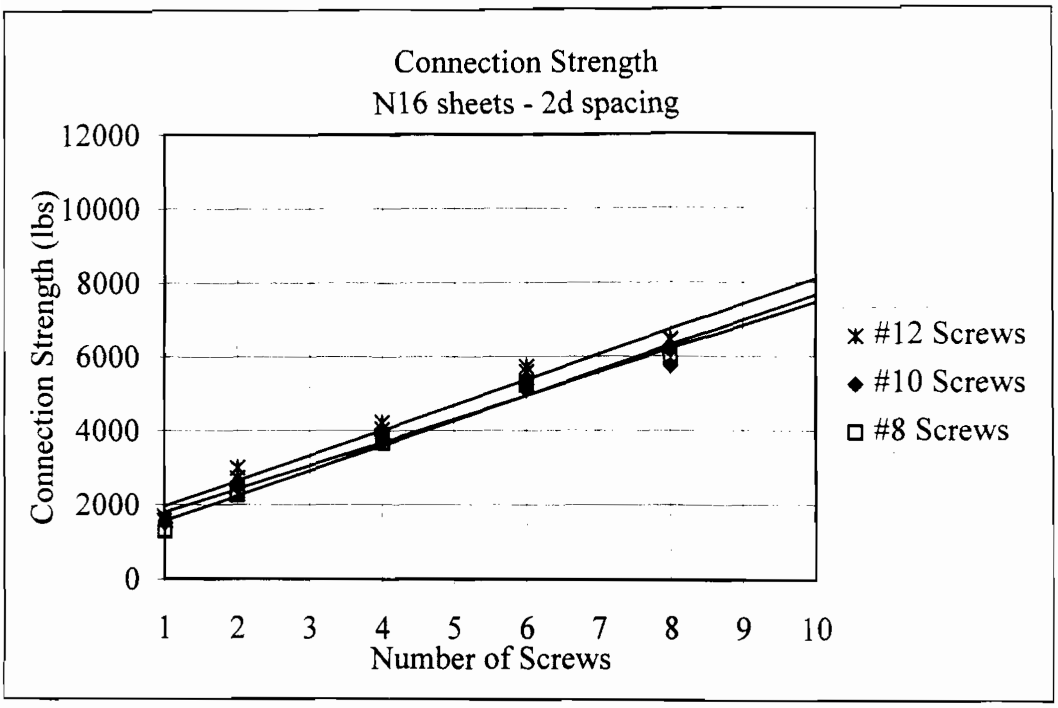


Figure I.4 Connection Strength - N16 Sheets - 2d Spacing - Screws vary

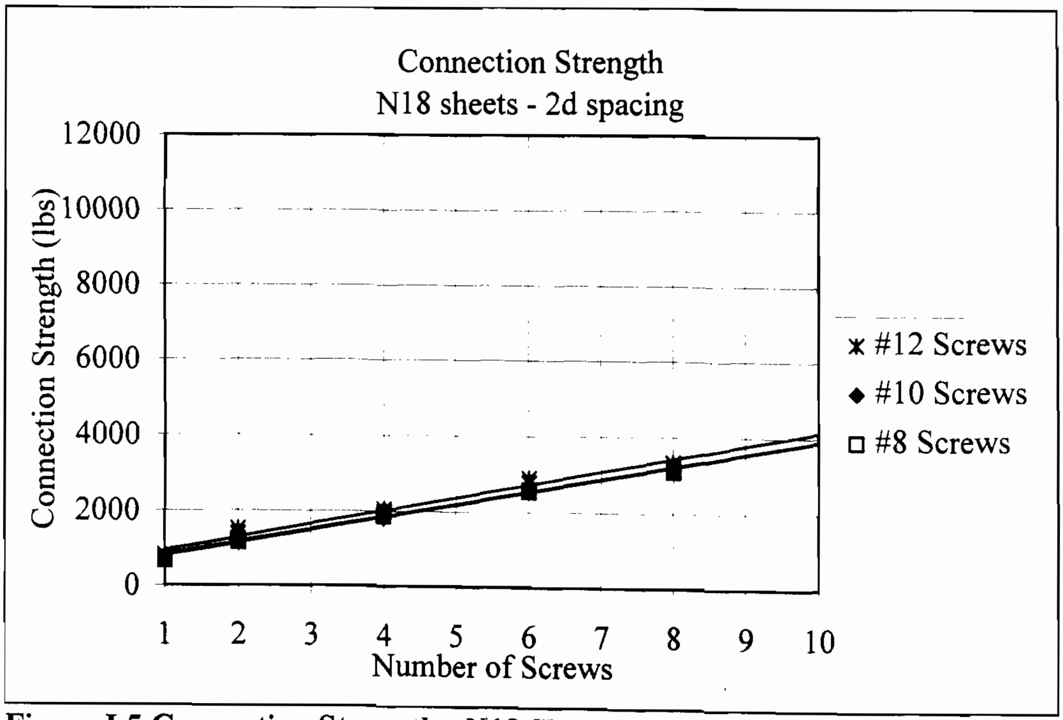


Figure I.5 Connection Strength - N18 Sheets - 2d Spacing - Screws vary

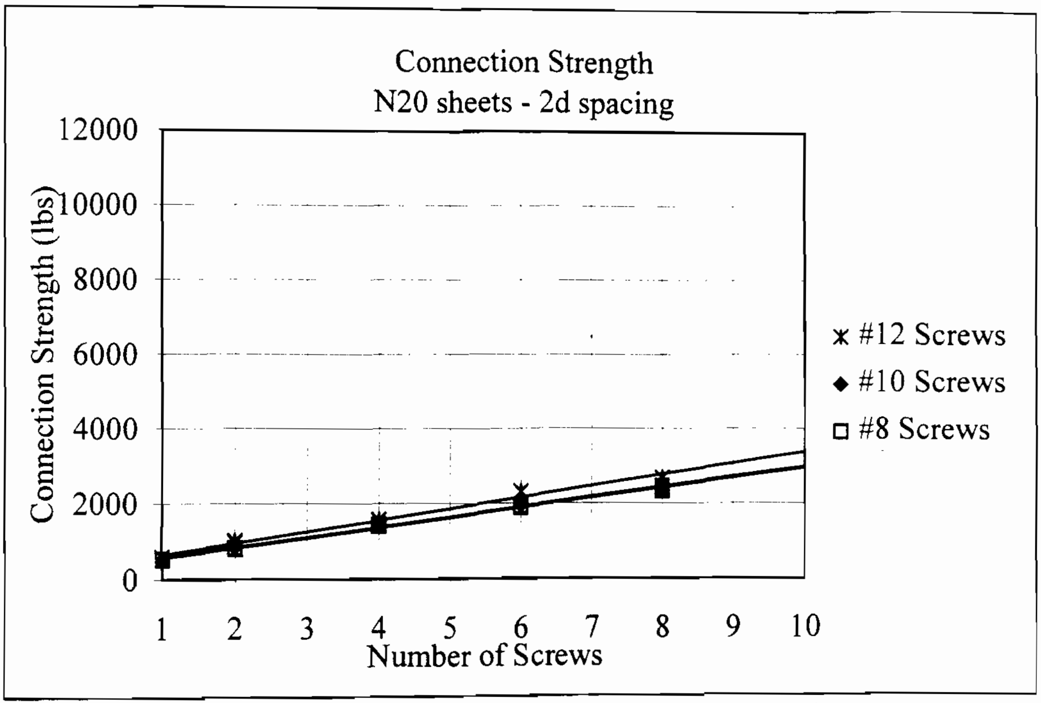


Figure I.6 Connection Strength - N20 Sheets - 2d Spacing - Screws vary

APPENDIX J

CONNECTION GRAPHS - BY SCREW SIZE

This appendix shows that connection strength varies strongly with sheet thickness. However, as will be made clear in Appendix M, the group effect does not vary with sheet thickness. See Appendix G for best fit equations.

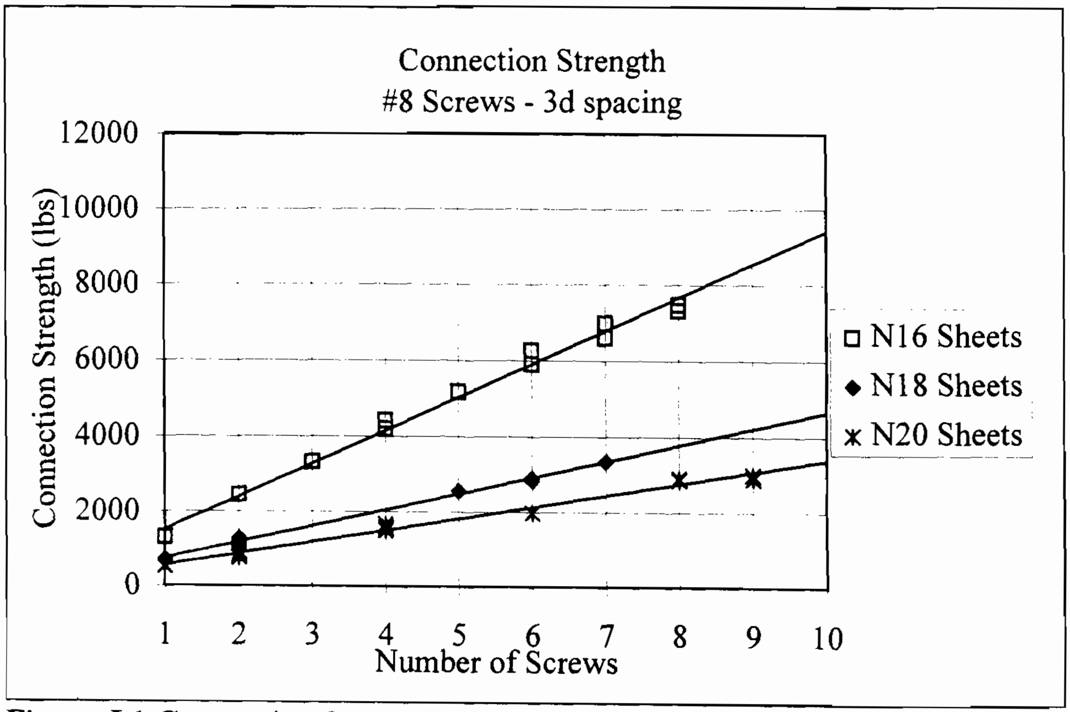


Figure J.1 Connection Strength - #8 Screws - 3d Spacing - Sheets vary

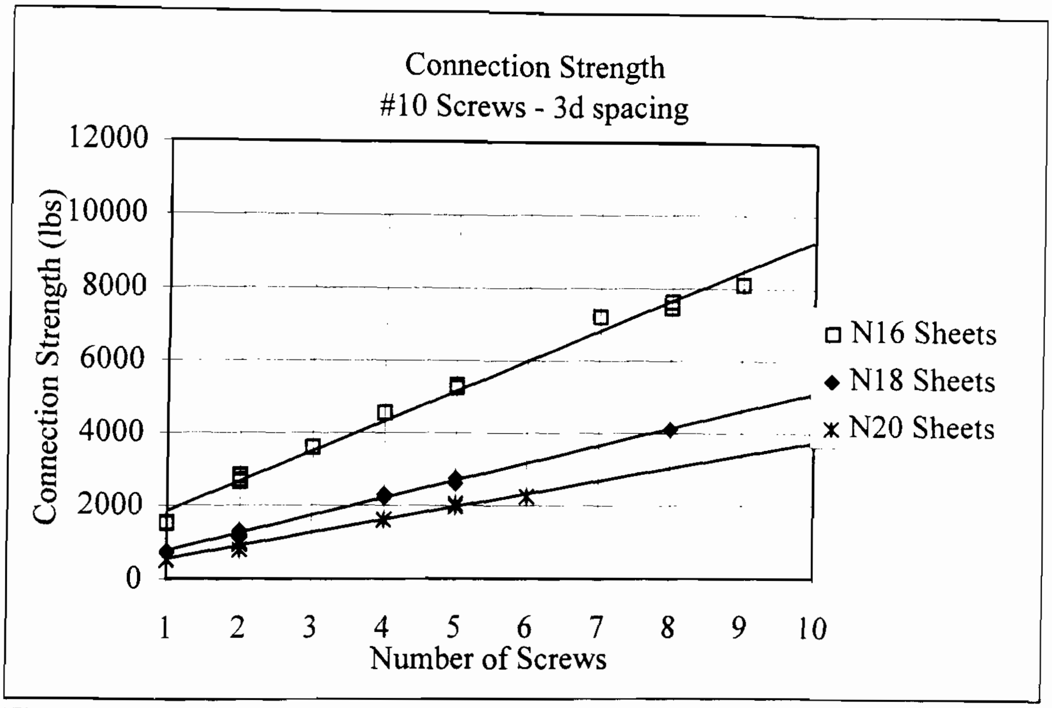


Figure J.2 Connection Strength - #10 Screws - 3d Spacing - Sheets vary

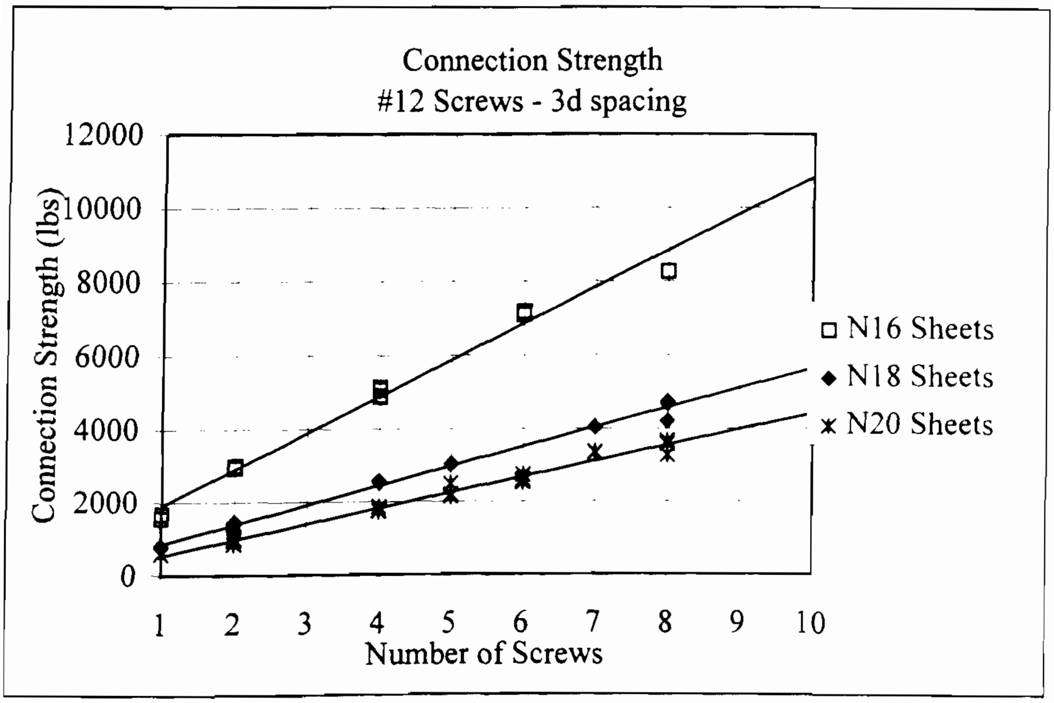


Figure J.3 Connection Strength - #12 Screws - 3d Spacing - Sheets vary

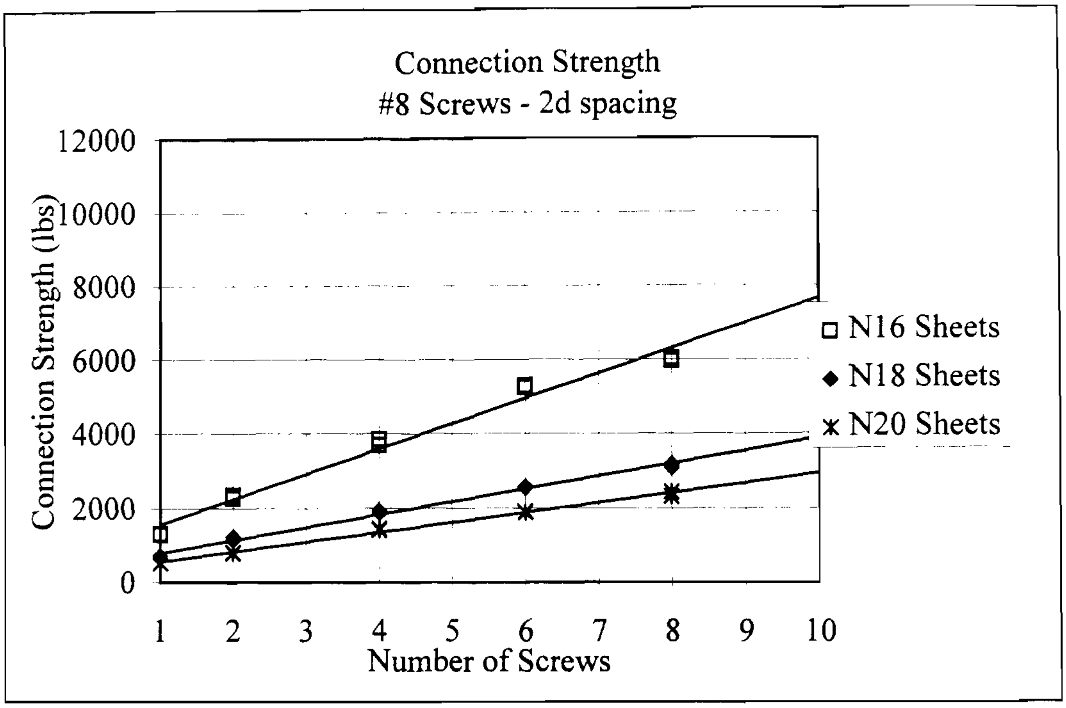


Figure J.4 Connection Strength - #8 Screws - 2d Spacing - Sheets vary

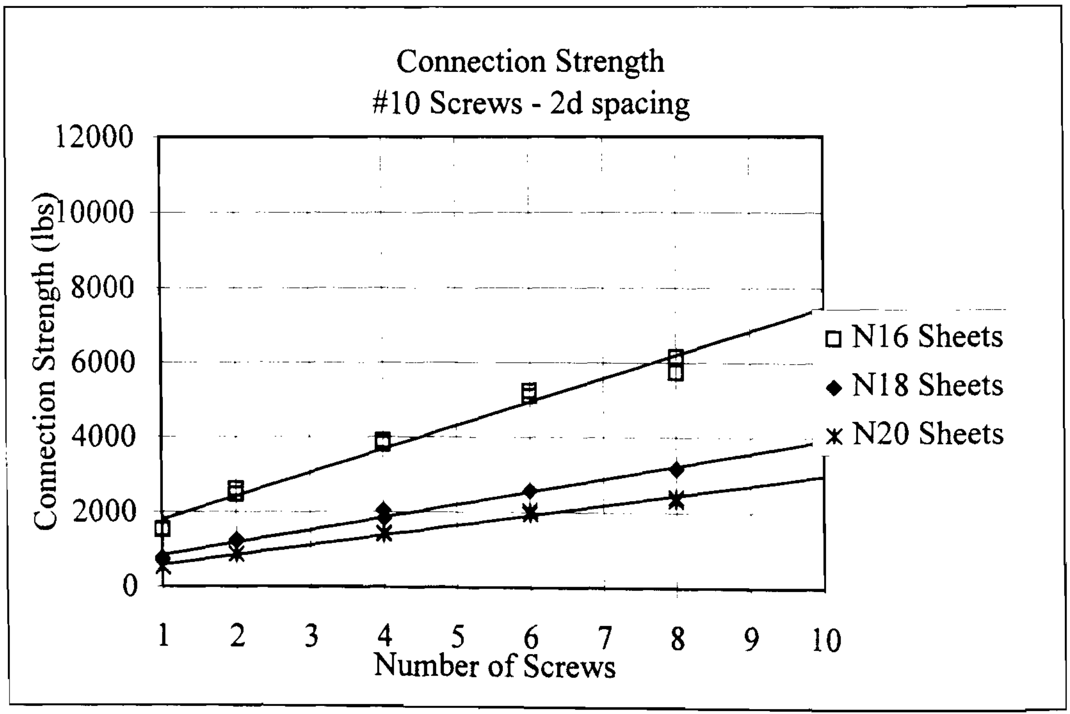


Figure J.5 Connection Strength - #10 Screws - 2d Spacing - Sheets vary

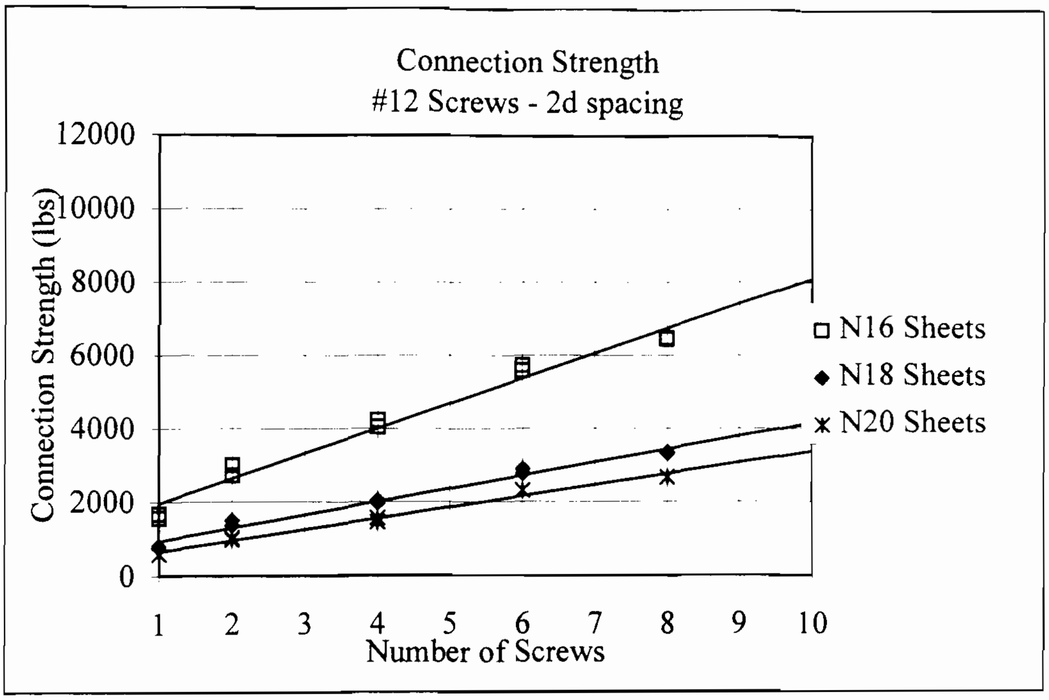


Figure J.6 Connection Strength - #12 Screws - 2d Spacing - Sheets vary

APPENDIX K

GROUP EFFECT GRAPHS - 3D VS. 2D SPACING

The group effect graphs of this appendix demonstrate that the group effect is a function of the screw spacing, 2d spacing giving a larger reduction in strength than 3d spacing. See Appendix G for best fit equations.

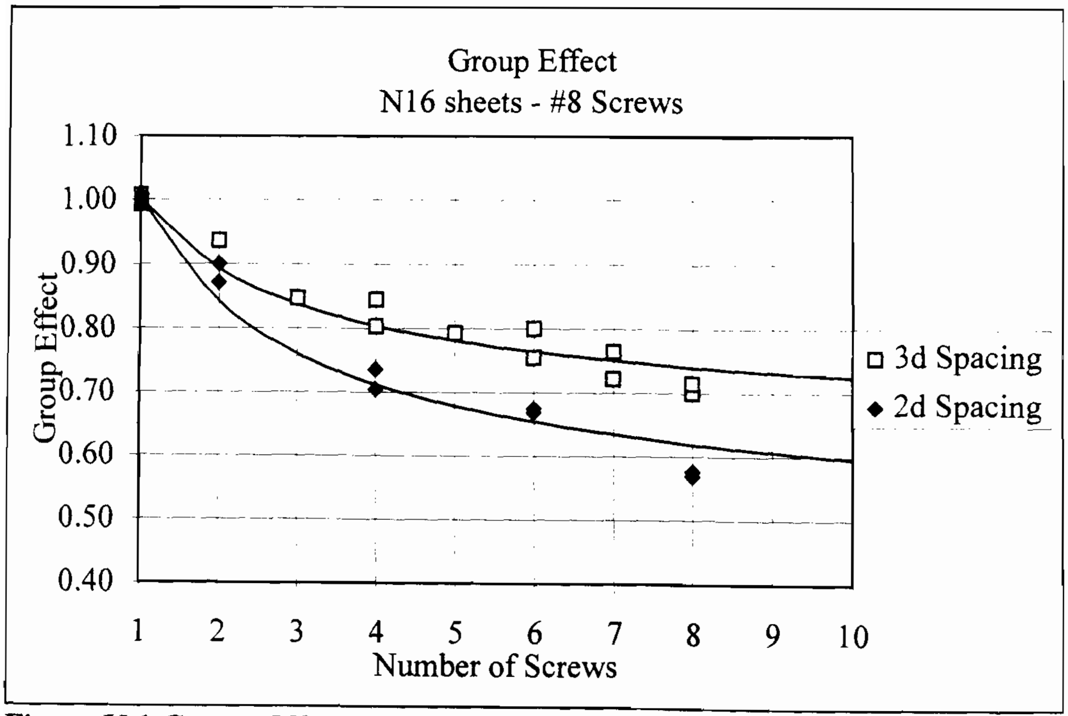


Figure K.1 Group Effect Graph - N16 Sheets - #8 Screws - 3d vs. 2d Spacing

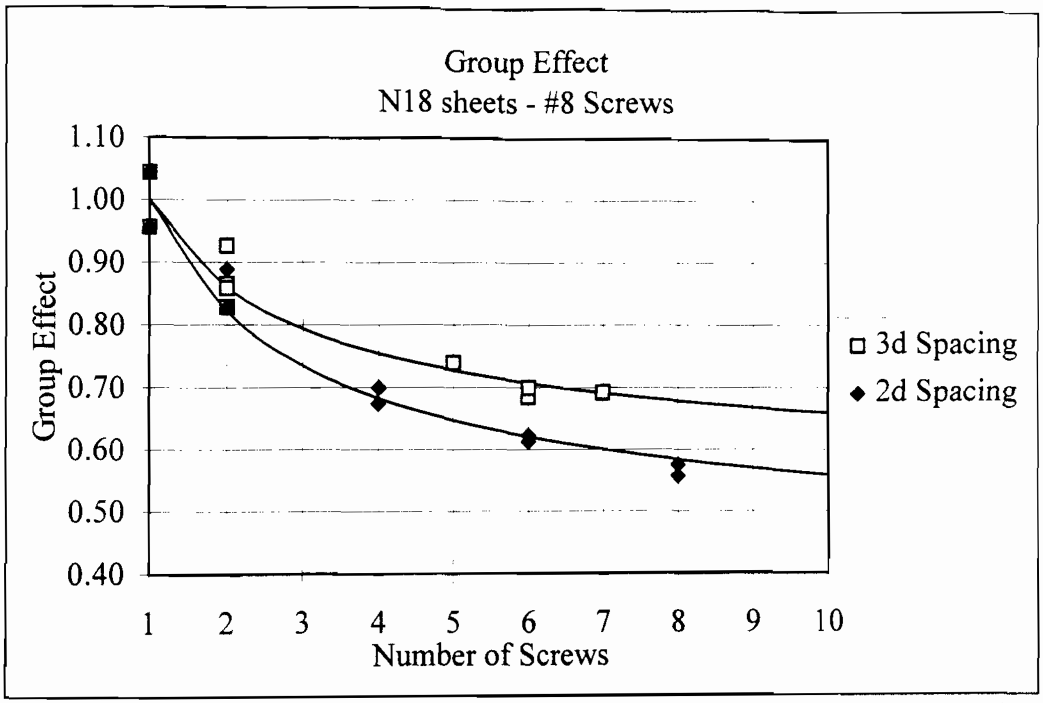


Figure K.2 Group Effect Graph - N18 Sheets - #8 Screws - 3d vs. 2d Spacing

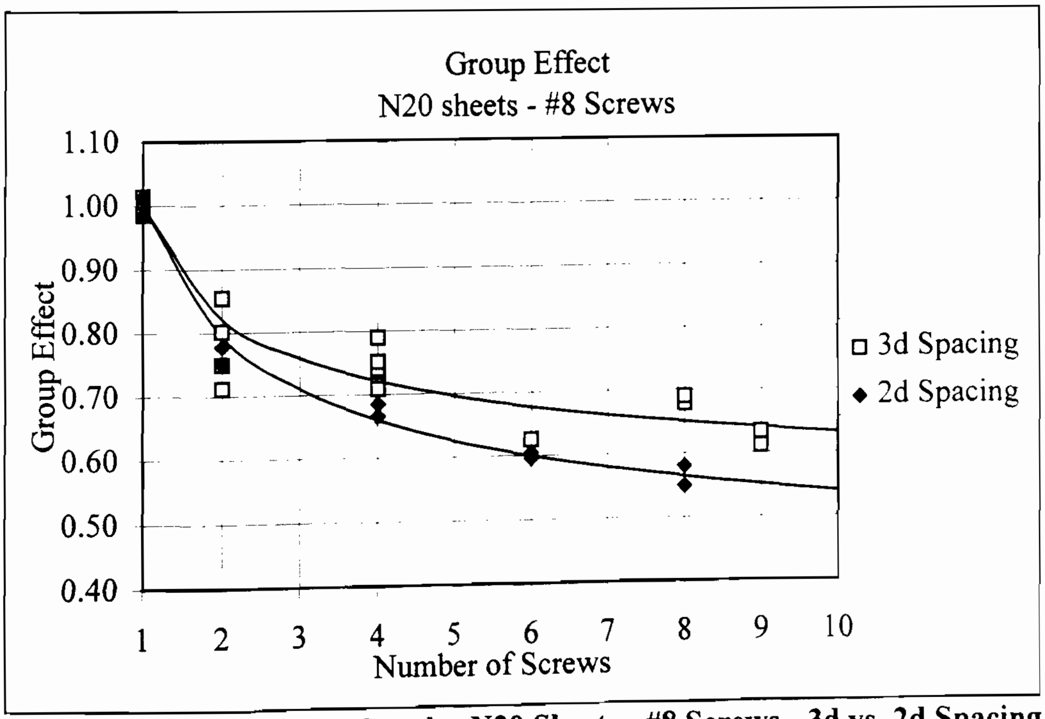


Figure K.3 Group Effect Graph - N20 Sheets - #8 Screws - 3d vs. 2d Spacing

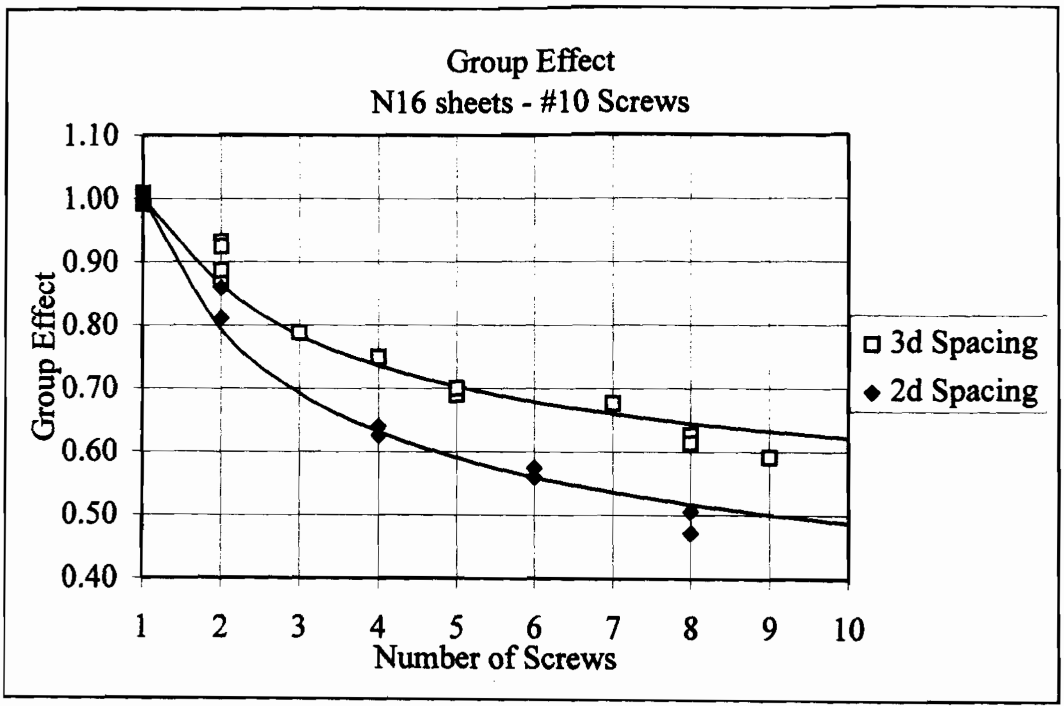


Figure K.4 Group Effect Graph - N16 Sheets - #10 Screws - 3d vs. 2d Spacing

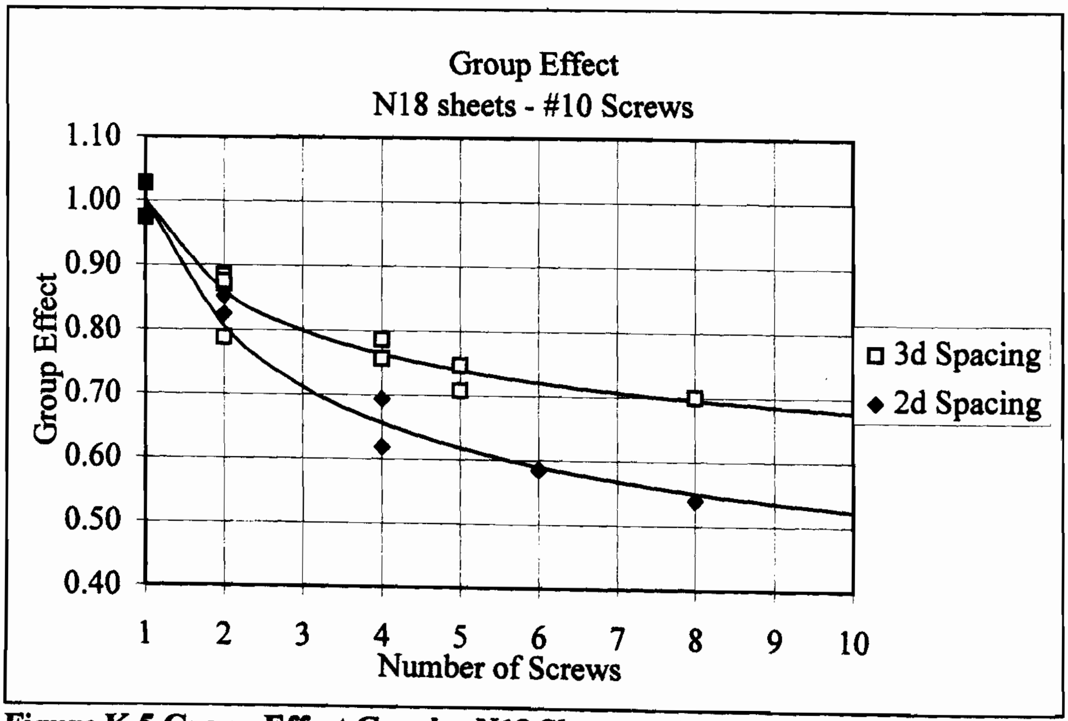


Figure K.5 Group Effect Graph - N18 Sheets - #10 Screws - 3d vs. 2d Spacing

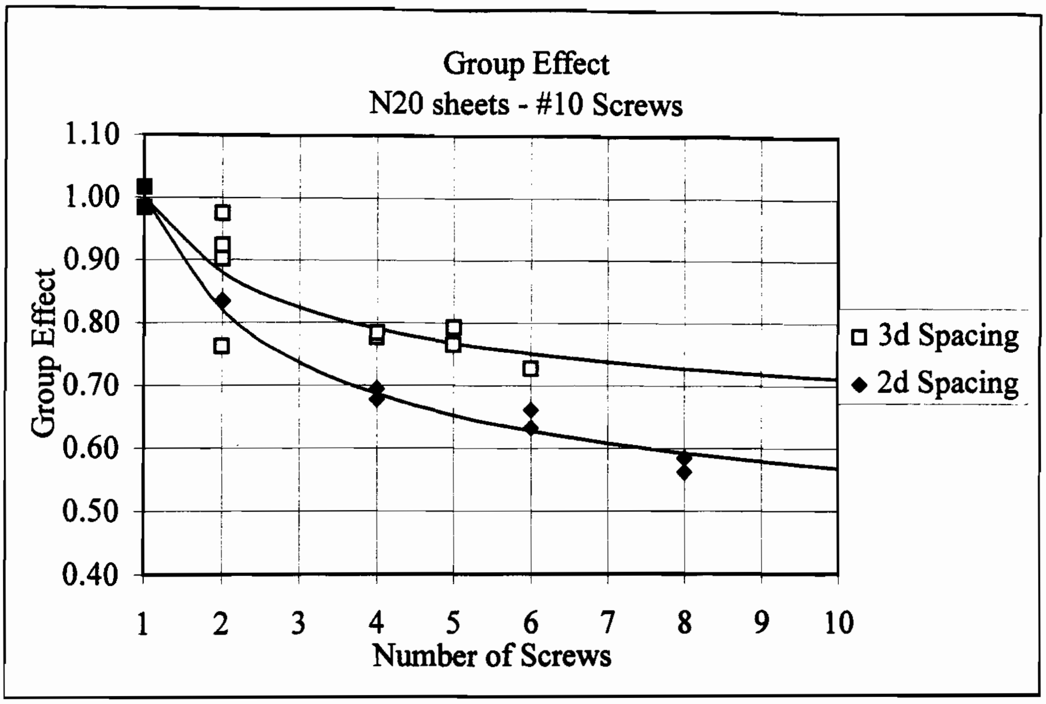


Figure K.6 Group Effect Graph - N20 Sheets - #10 Screws - 3d vs. 2d Spacing

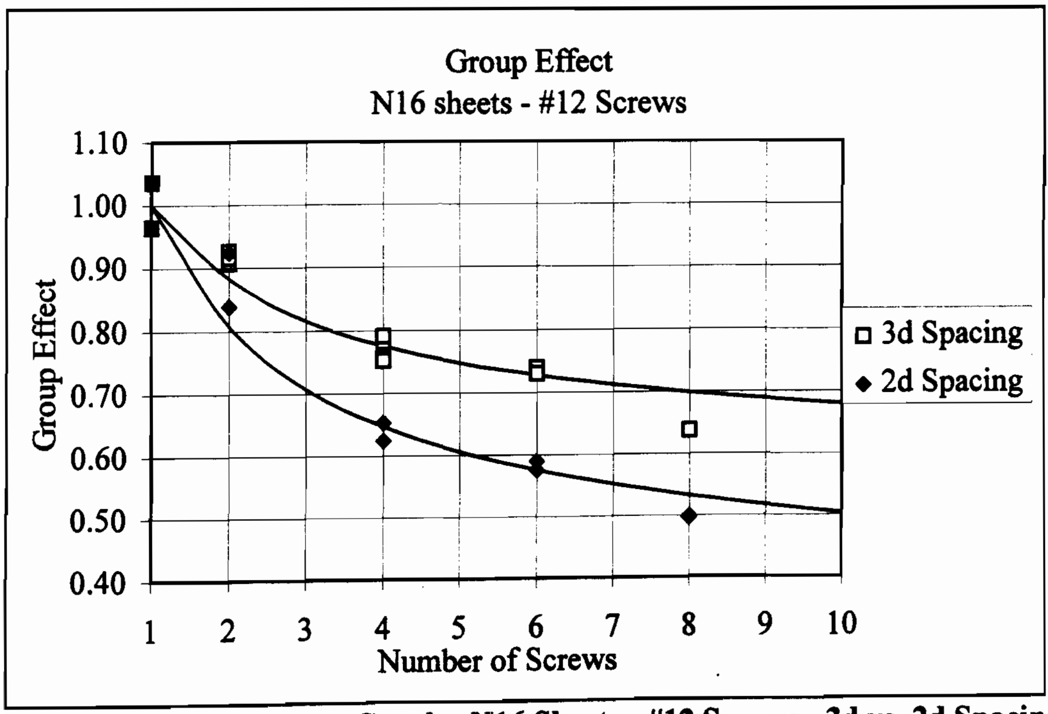


Figure K.7 Group Effect Graph - N16 Sheets - #12 Screws - 3d vs. 2d Spacing

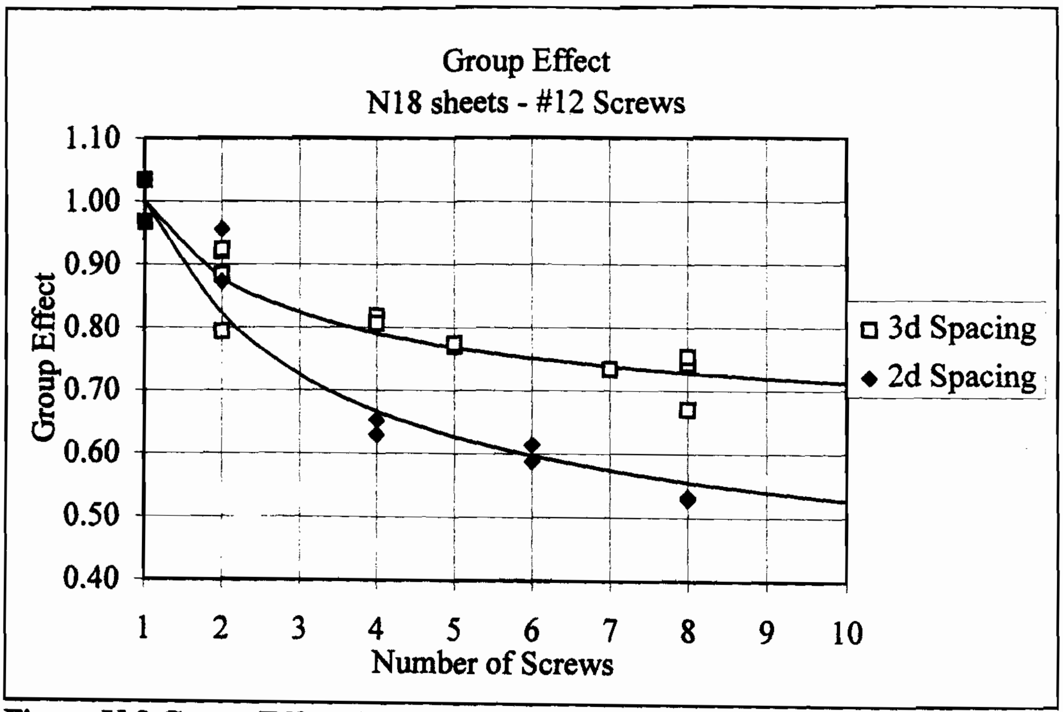


Figure K.8 Group Effect Graph - N18 Sheets - #12 Screws - 3d vs. 2d Spacing

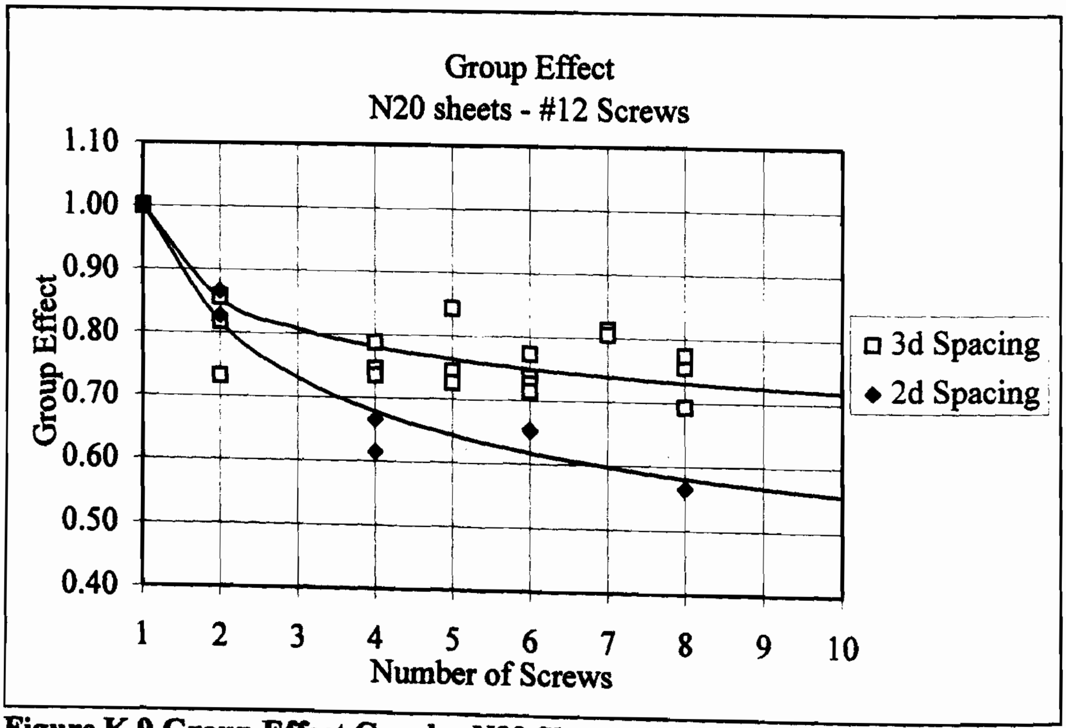


Figure K.9 Group Effect Graph - N20 Sheets - #12 Screws - 3d vs. 2d Spacing

APPENDIX L

GROUP EFFECT GRAPHS - BY SHEET THICKNESS

This appendix shows that the group effect is not significantly affected by the screw size. See Appendix G for best fit equations.

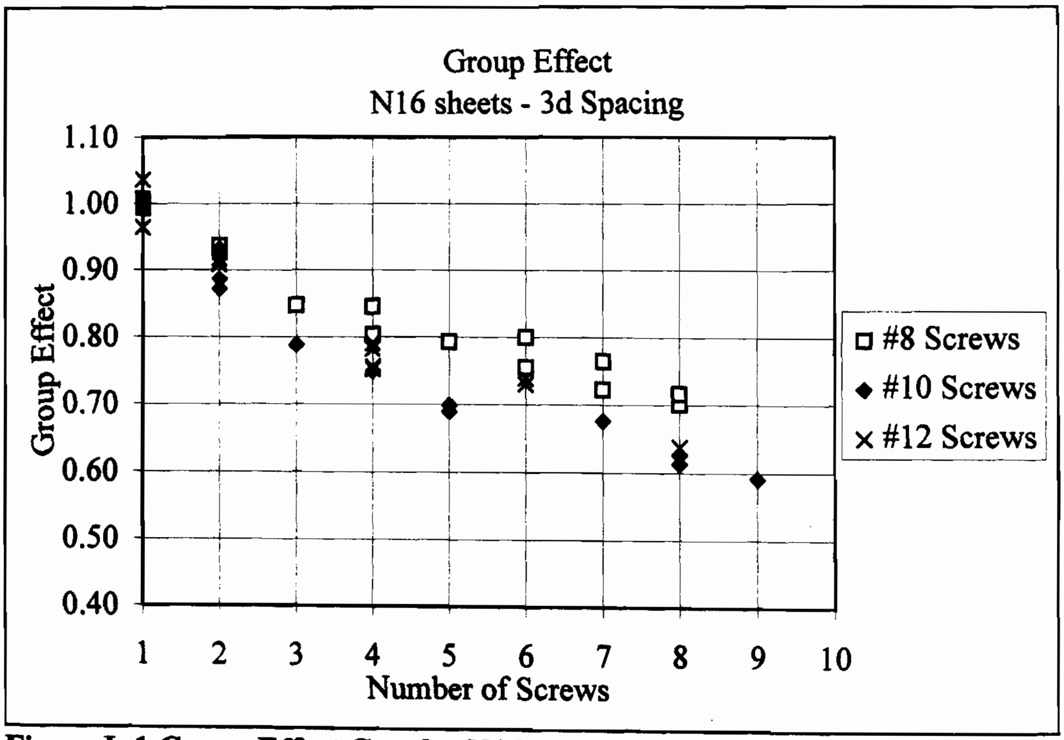


Figure L.1 Group Effect Graph - N16 Sheets - 3d Spacing - Screws vary

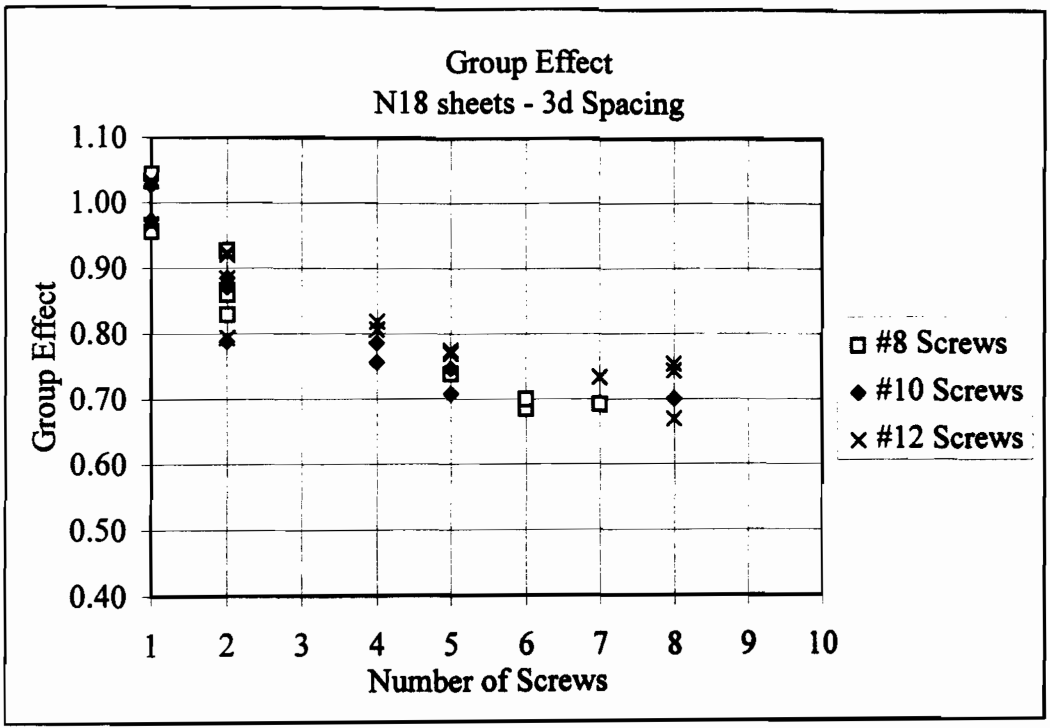


Figure L.2 Group Effect Graph - N18 Sheets - 3d Spacing - Screws vary

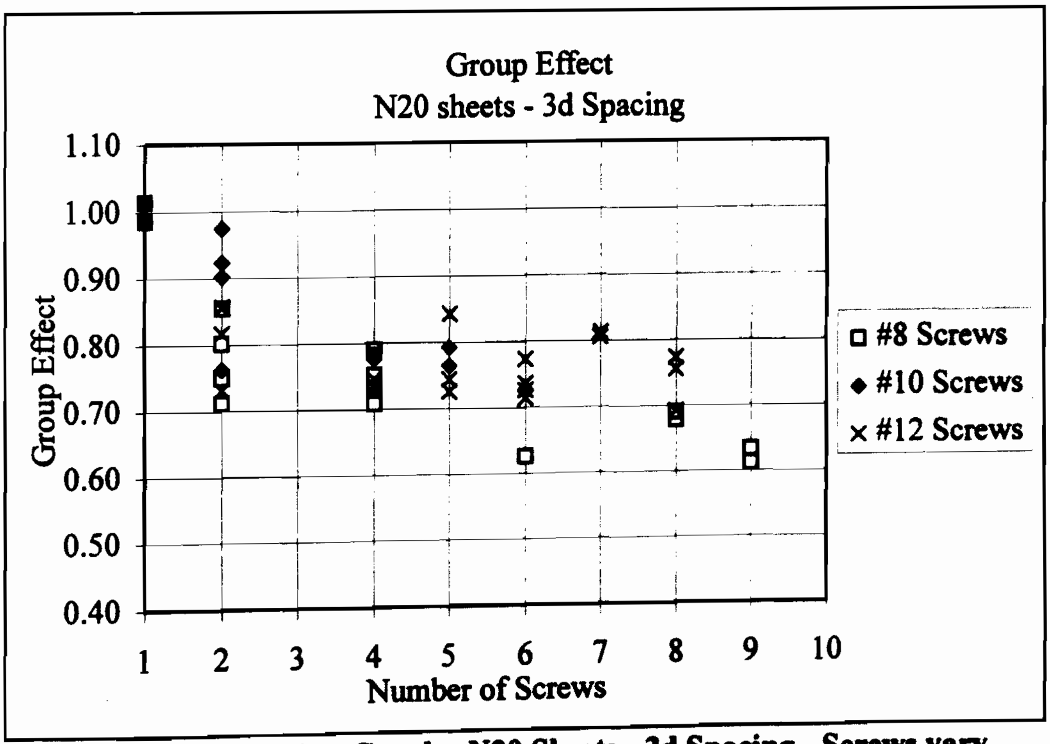


Figure L.3 Group Effect Graph - N20 Sheets - 3d Spacing - Screws vary

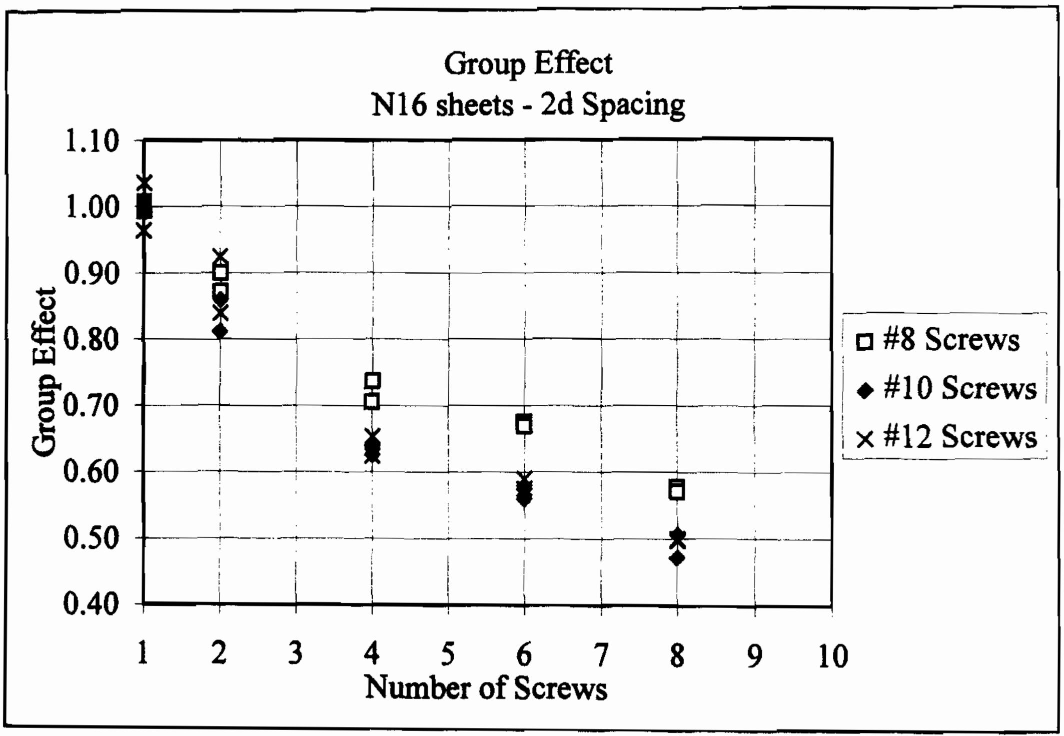


Figure L.4 Group Effect Graph - N16 Sheets - 2d Spacing - Screws vary

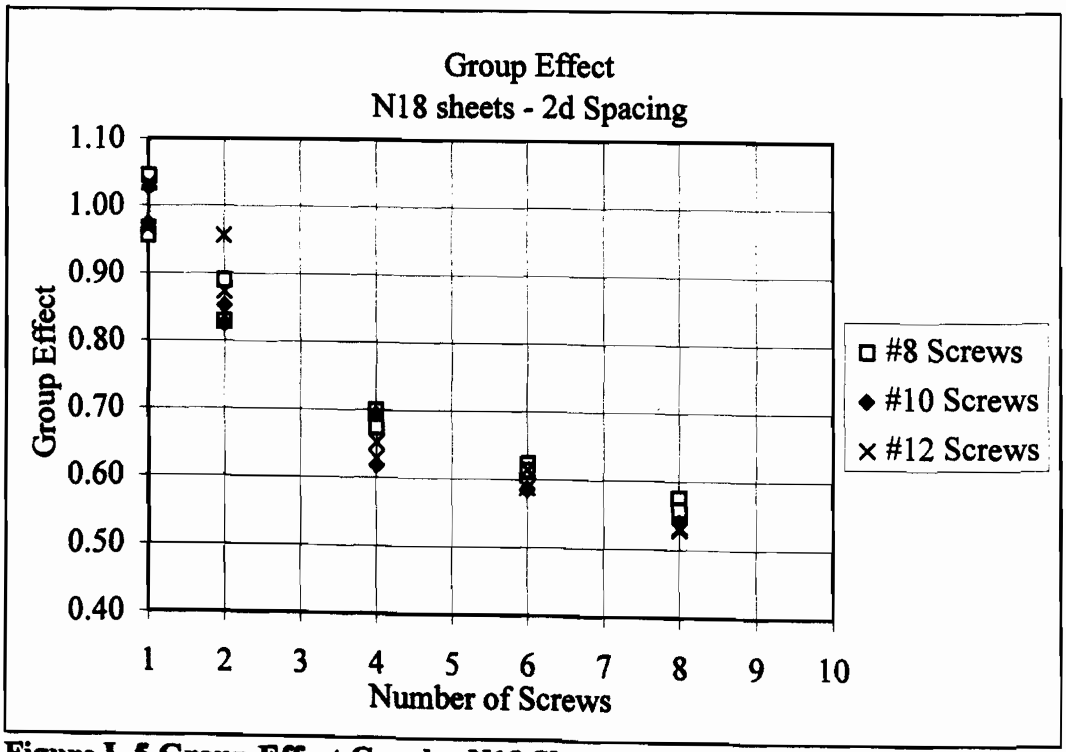


Figure L.5 Group Effect Graph - N18 Sheets - 2d Spacing - Screws vary

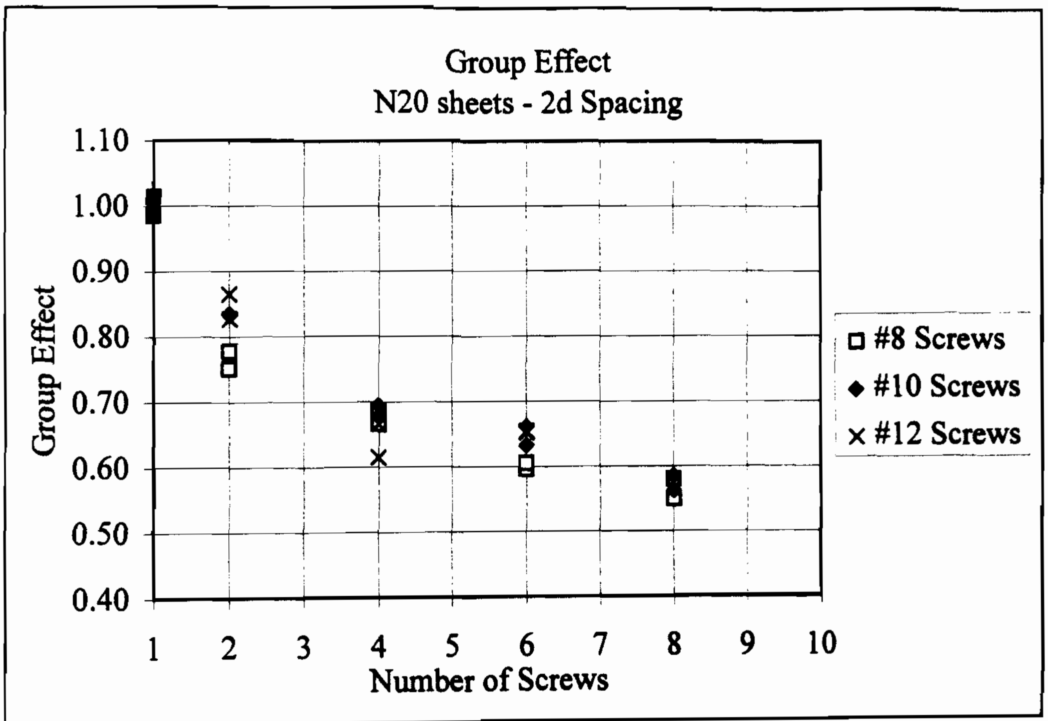


Figure L.6 Group Effect Graph - N20 Sheets - 2d Spacing - Screws vary

APPENDIX M

GROUP EFFECT GRAPHS - BY SCREW SIZE

This appendix indicates that the group effect does not vary significantly with a change in sheet thickness. See Appendix G for best fit equations.

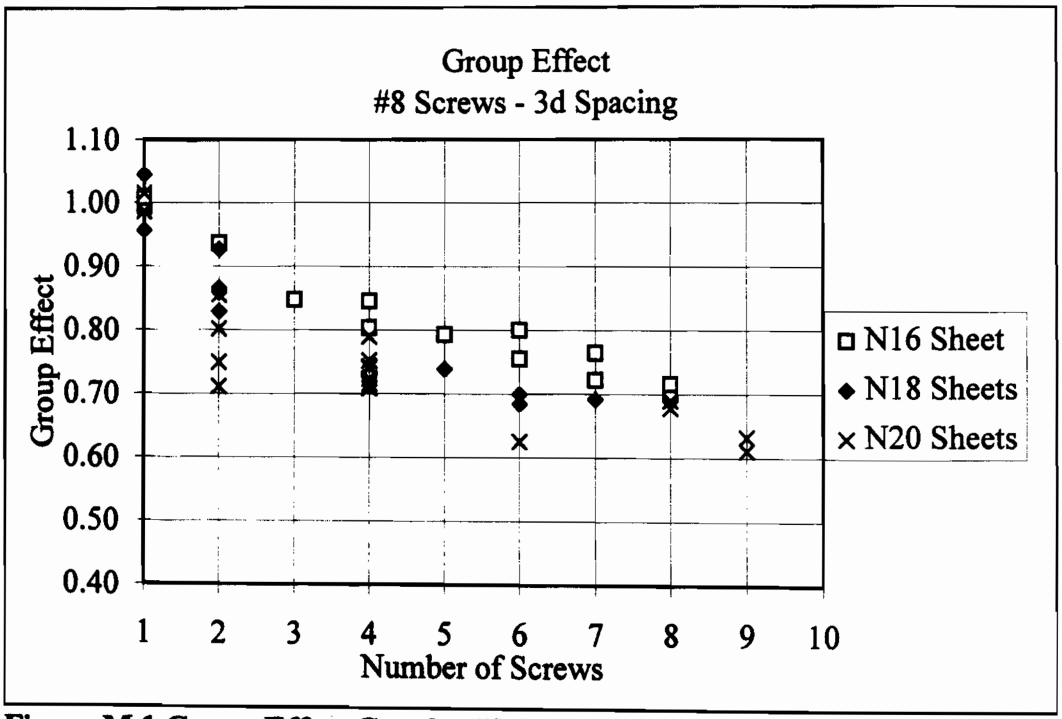


Figure M.1 Group Effect Graph - #8 Screws - 3d Spacing - Sheets vary

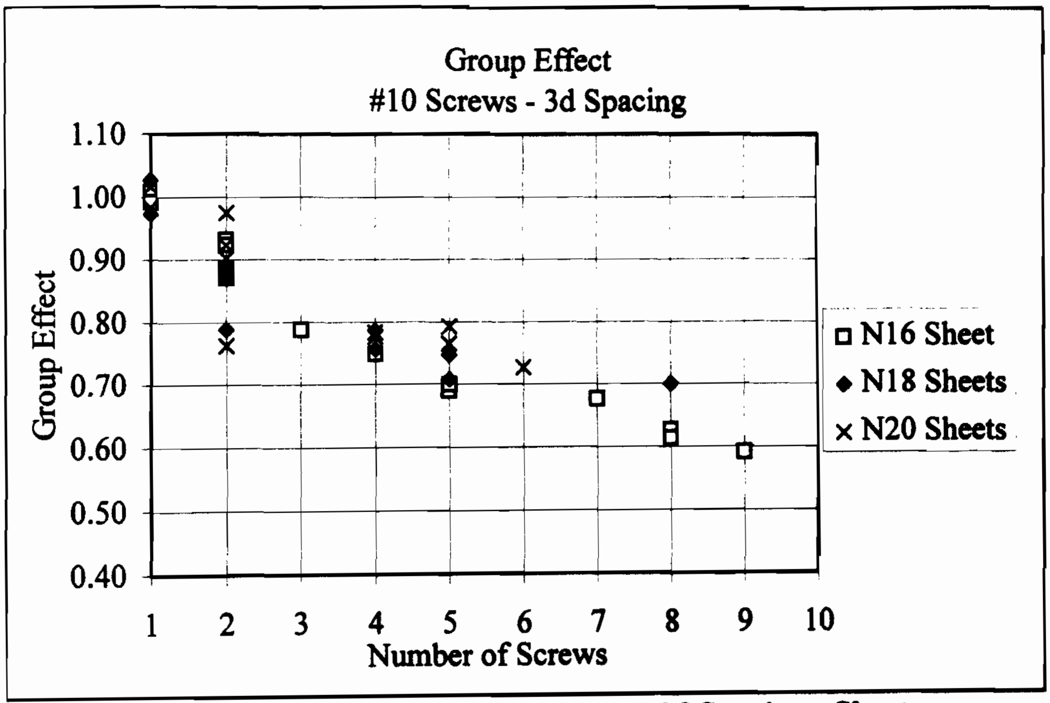


Figure M.2 Group Effect Graph - #10 Screws - 3d Spacing - Sheets vary

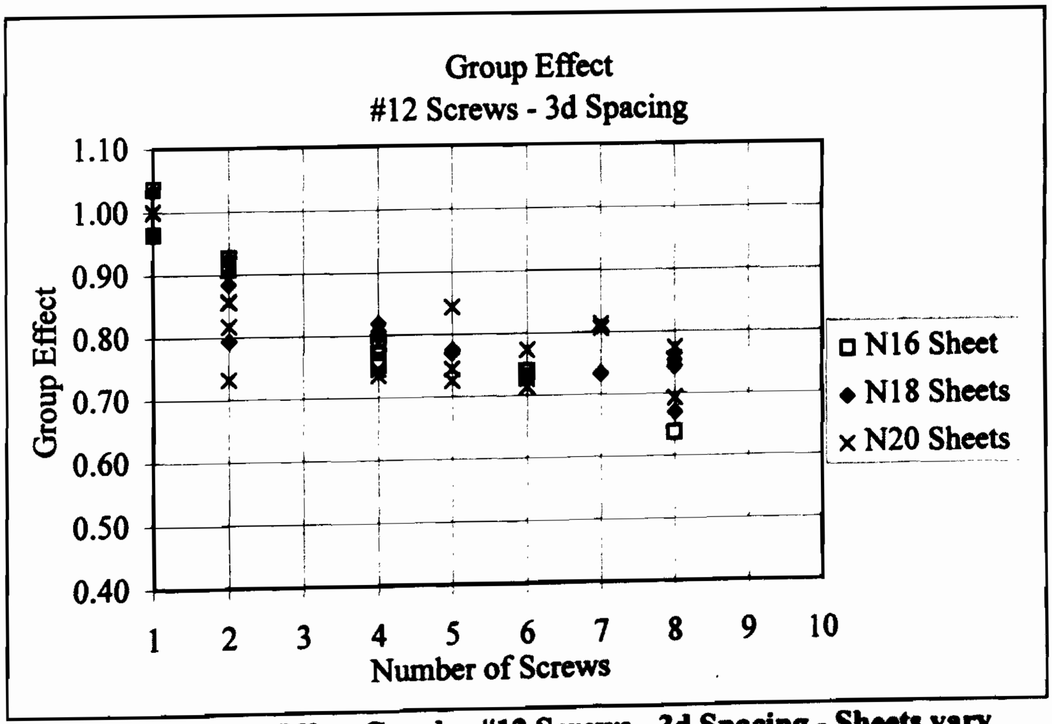


Figure M.3 Group Effect Graph - #12 Screws - 3d Spacing - Sheets vary

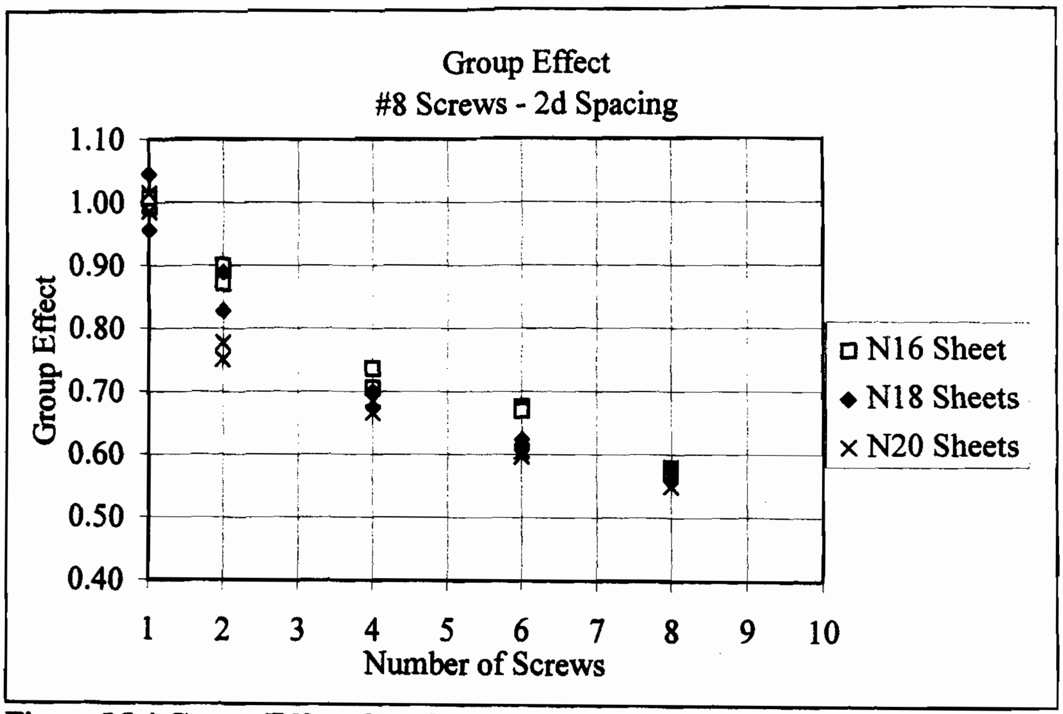


Figure M.4 Group Effect Graph - #8 Screws - 2d Spacing - Sheets vary

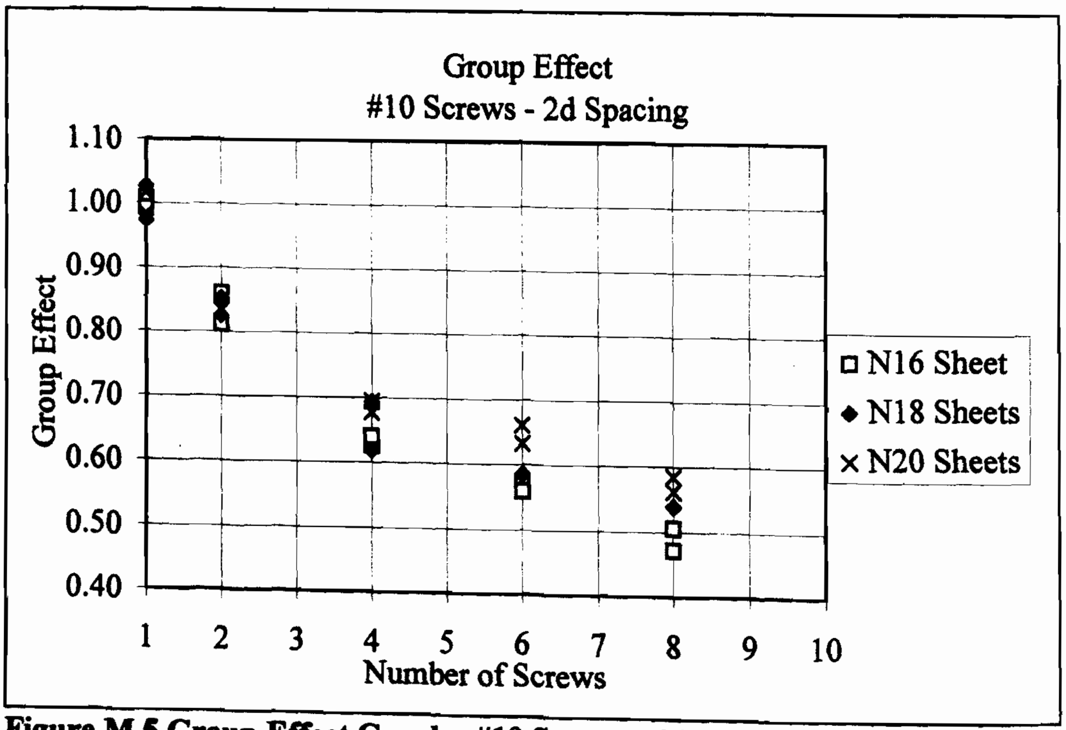


Figure M.5 Group Effect Graph - #10 Screws - 2d Spacing - Sheets vary

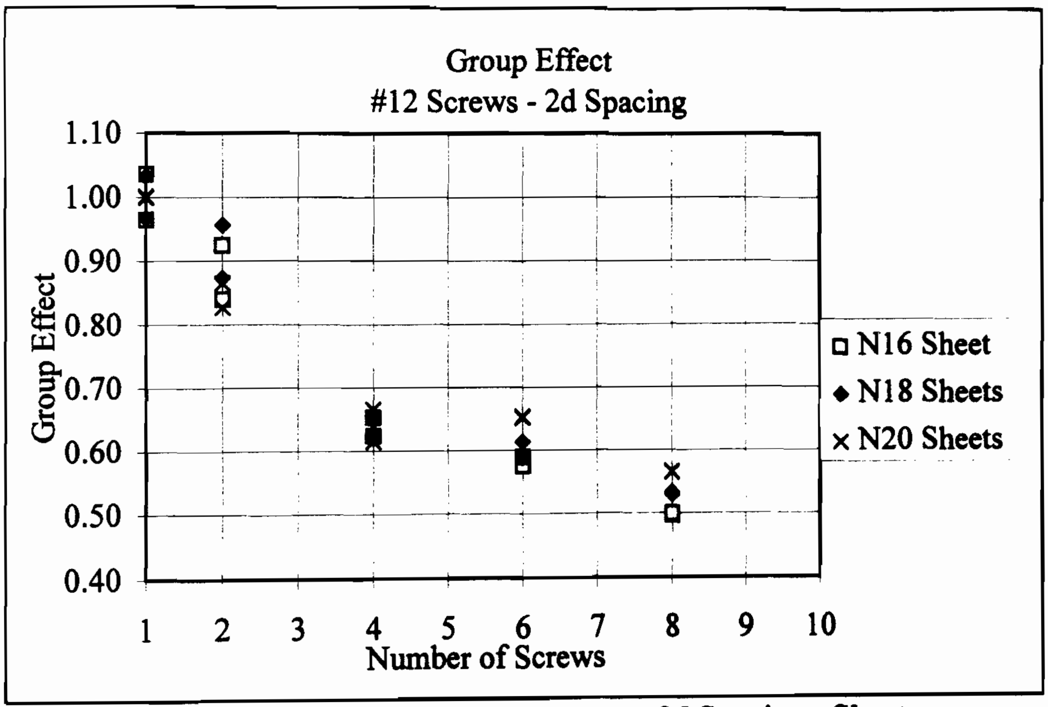


Figure M.6 Group Effect Graph - #12 Screws - 2d Spacing - Sheets vary

APPENDIX N

TABLES COMPARING DATA TO UMR DESIGN MODELS AND AISI SPECIFICATION EQUATIONS

See Equations (4-6) through (4-9) for Design Model 1, and Equations (4-10) through (4-14) for Design Model 2.

Table N.1 Sokol 3d Data - Comparing Tested to Computed Strength

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
N16-3-11	0.96	0.96	0.89
N16-50-10	0.97	0.97	0.90
N16-1-9	1.04	1.04	0.84
N16-2-1	1.02	1.02	0.76
N16-2-5	1.01	1.01	0.72
N16-2-9	1.06	1.06	0.76
N16-51-1	1.03	1.03	0.71
N16-50-9	1.00	1.00	0.68
N16-51-8	1.06	1.06	0.72
N16-51-2	0.98	0.98	0.65
N16-51-9	1.04	1.04	0.68
N16-50-7	0.97	0.97	0.63
N16-51-5	0.99	0.99	0.64
N18-1-9	1.14	1.14	1.13
N18-52-9	1.04	1.04	1.03
N18-1-1	1.04	1.04	0.89
N18-2-4	1.09	1.09	0.93
N18-1-2	1.08	1.08	0.93
N18-2-5	1.17	1.17	1.00
N18-1-3	1.08	1.08	0.80
N18-4-3	1.03	1.03	0.74
N18-2-6	1.05	1.05	0.75
N18-50-1	1.06	1.06	0.75
N18-50-7	1.06	1.06	0.75
N20-2-10	1.07	1.07	1.15
N20-4-9	1.10	1.10	1.18
N20-2-5	0.89	0.89	0.83
N20-2-6	0.94	0.94	0.87
N20-2-7	1.07	1.07	1.00
N20-2-8	1.00	1.00	0.93
N20-3-1	1.02	1.02	0.84
N20-3-2	1.01	1.01	0.83

Test	**Model 1** P_{test}/P_{comp}	**Model 2** P_{test}/P_{comp}	**AISI** P_{test}/P_{comp}
N20-3-3	1.05	1.05	0.86
N20-3-4	1.04	1.04	0.86
N20-50-8	1.00	1.00	0.83
N20-3-6	1.11	1.11	0.92
N20-3-8	1.06	1.06	0.88
N20-3-5	0.93	0.93	0.73
N20-51-1	1.05	1.05	0.79
N20-51-6	1.07	1.07	0.80
N20-51-5	0.96	0.96	0.71
N20-51-7	0.99	0.99	0.74
N16-4-11	1.04	1.04	0.99
N16-2-10	1.02	1.02	0.98
N16-1-10	1.04	1.04	0.86
N16-3-1	1.06	1.06	0.87
N16-3-2	1.11	1.11	0.92
N16-3-3	1.10	1.10	0.91
N16-2-3	1.01	1.01	0.77
N16-2-6	1.01	1.01	0.74
N16-2-4	0.96	0.96	0.68
N16-2-7	0.97	0.97	0.69
N16-50-8	0.98	0.98	0.67
N16-52-3	0.92	0.92	0.62
N16-52-4	0.91	0.91	0.60
N16-52-5	0.88	0.88	0.58
N18-52-8	1.03	1.03	1.05
N18-4-12	1.08	1.08	1.11
N18-1-7	1.06	1.06	0.94
N18-2-7	0.96	0.96	0.85
N18-2-8	1.08	1.08	0.95
N18-2-9	1.07	1.07	0.94
N18-1-10	1.04	1.04	0.82
N18-3-1	1.08	1.08	0.85
N18-1-8	1.00	1.00	0.76
N18-2-1	1.06	1.06	0.81
N18-50-3	1.05	1.05	0.76
N20-3-10	0.95	0.95	1.06
N20-54-1	0.98	0.98	1.09
N20-3-9	0.85	0.85	0.82

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
N20-4-4	1.03	1.03	0.99
N20-4-5	1.00	1.00	0.97
N20-4-6	1.08	1.08	1.05
N20-4-2	0.97	0.97	0.83
N20-4-7	0.98	0.98	0.84
N20-4-3	0.99	0.99	0.82
N20-4-8	1.02	1.02	0.85
N20-4-1	0.96	0.96	0.78
N16-4-9	0.95	0.95	0.94
N16-1-11	1.02	1.02	1.01
N16-1-4	1.04	1.04	0.88
N16-3-4	1.06	1.06	0.90
N16-1-1	1.04	1.04	0.89
N16-1-2	1.05	1.05	0.89
N16-1-5	0.97	0.97	0.73
N16-1-6	0.97	0.97	0.73
N16-1-7	1.00	1.00	0.76
N16-1-8	1.02	1.02	0.77
N16-50-5	1.01	1.01	0.72
N16-50-6	0.99	0.99	0.71
N16-52-6	0.90	0.90	0.62
N18-52-7	1.04	1.04	1.11
N18-3-10	0.97	0.97	1.04
N18-1-4	1.07	1.07	0.99
N18-3-2	0.92	0.92	0.85
N18-1-5	1.03	1.03	0.95
N18-3-3	1.07	1.07	0.99
N18-3-4	1.07	1.07	0.88
N18-3-5	1.05	1.05	0.86
N18-3-6	1.04	1.04	0.83
N18-3-7	1.05	1.05	0.83
N18-50-4	1.03	1.03	0.79
N18-51-2	1.04	1.04	0.79
N18-50-5	1.07	1.07	0.80
N18-51-3	1.08	1.08	0.81
N18-51-4	0.96	0.96	0.72
N20-5-12	0.98	0.98	1.15
N20-1-11	0.97	0.97	1.14

Test	**Model 1** P_{test}/P_{comp}	**Model 2** P_{test}/P_{comp}	**AISI** P_{test}/P_{comp}
N20-1-7	0.92	0.92	0.93
N20-1-8	0.82	0.82	0.84
N20-1-9	0.97	0.97	0.98
N20-1-10	0.96	0.96	0.98
N20-1-1	0.95	0.95	0.85
N20-1-2	1.00	1.00	0.90
N20-1-3	0.93	0.93	0.84
N20-1-4	0.93	0.93	0.84
N20-2-1	0.98	0.98	0.85
N20-2-2	0.95	0.95	0.83
N20-2-4	1.11	1.11	0.96
N20-50-6	1.04	1.04	0.88
N20-50-7	0.99	0.99	0.84
N20-1-5	0.98	0.98	0.83
N20-1-6	0.96	0.96	0.82
N20-50-4	1.11	1.11	0.93
N20-50-5	1.10	1.10	0.92
N20-50-2	1.05	1.05	0.86
N20-50-3	1.08	1.08	0.89
N20-52-2	0.96	0.96	0.79
Mean	**1.01**	**1.01**	**0.86**
C.O.V.	**0.06**	**0.06**	**0.15**

See Equations (4-6) through (4-9) for Design Model 1, and Equations (4-10) through (4-14) for Design Model 2.

Table N.2 Sokol 2d Data - Comparing Tested to Computed Strength

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
N16-3-6	1.07	1.08	0.81
N16-3-7	1.03	1.05	0.78
N16-3-8	1.06	1.07	0.66
N16-3-9	1.02	1.03	0.63
N16-52-7	1.08	1.08	0.60
N16-52-8	1.07	1.07	0.60
N16-52-9	0.99	0.98	0.52
N16-53-1	0.97	0.97	0.51
N18-3-8	1.19	1.20	0.96
N18-4-1	1.11	1.12	0.89
N18-3-9	1.14	1.15	0.75
N18-4-2	1.10	1.11	0.73
N18-51-5	1.12	1.12	0.67
N18-51-6	1.10	1.11	0.66
N18-51-7	1.11	1.10	0.62
N18-51-8	1.07	1.07	0.60
N20-5-4	1.00	1.01	0.87
N20-52-3	1.03	1.05	0.91
N20-5-5	1.08	1.09	0.78
N20-52-4	1.11	1.12	0.80
N20-52-5	1.07	1.07	0.69
N20-52-6	1.08	1.08	0.70
N20-52-7	1.11	1.10	0.68
N20-52-8	1.05	1.04	0.64
N16-3-10	1.03	1.04	0.80
N16-4-1	1.09	1.10	0.85
N16-4-2	0.97	0.98	0.62
N16-4-3	0.99	1.00	0.63
N16-53-2	0.98	0.98	0.56
N16-53-3	0.96	0.96	0.55
N16-53-4	0.92	0.92	0.50
N16-53-5	0.86	0.86	0.46

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
N18-4-8	1.07	1.08	0.89
N18-4-9	1.10	1.12	0.92
N18-4-10	0.97	0.98	0.67
N18-4-11	1.09	1.10	0.75
N18-52-3	1.02	1.02	0.63
N18-52-4	1.02	1.02	0.63
N18-52-5	1.01	1.00	0.58
N18-52-6	1.00	1.00	0.58
N20-5-6	0.99	1.00	0.90
N20-53-4	0.98	0.99	0.89
N20-5-7	0.97	0.98	0.73
N20-53-5	1.00	1.01	0.75
N20-52-9	1.05	1.05	0.71
N20-53-1	1.01	1.01	0.68
N20-53-2	0.95	0.95	0.60
N20-53-3	0.99	0.99	0.63
N16-4-8	1.02	1.03	0.82
N16-4-5	1.12	1.13	0.90
N16-4-6	0.92	0.93	0.61
N16-4-7	0.96	0.97	0.64
N16-53-6	0.94	0.94	0.56
N16-53-7	0.96	0.96	0.57
N16-53-8	0.87	0.86	0.48
N16-53-9	0.87	0.86	0.49
N18-4-4	1.18	1.19	1.02
N18-4-5	1.08	1.09	0.94
N18-4-6	0.98	0.99	0.70
N18-4-7	0.94	0.95	0.67
N18-51-9	1.02	1.02	0.66
N18-52-1	0.98	0.98	0.63
N18-51-10	0.94	0.93	0.57
N18-52-2	0.94	0.94	0.57
N20-5-8	0.99	1.00	0.95
N20-5-9	1.04	1.05	0.99
N20-5-10	0.90	0.90	0.70
N20-5-11	0.97	0.98	0.76
N20-53-6	1.05	1.06	0.75
N20-53-7	1.05	1.05	0.75

N20-53-8	0.97	0.97	0.65
N20-53-9	0.97	0.97	0.65
Mean	**1.02**	**1.02**	**0.70**
C.O.V.	**0.07**	**0.07**	**0.19**

See Equations (4-6) through (4-9) for Design Model 1, and Equations (4-10) through (4-14) for Design Model 2.

Table N.3 Rogers and Hancock Data - Comparing Tested to Computed Strength

Pattern	**Screw**	**Model 1** P_{test}/P_{comp}	**Model 2** P_{test}/P_{comp}	**AISI** P_{test}/P_{comp}
S2L-L	8-8x12	1.15	1.15	1.21
S2T-L	8-8x12	1.24	1.24	1.31
S4S-L	8-8x12	1.25	1.25	1.17
S2L-L	10-16x16	1.15	1.15	1.28
S2T-L	10-16x16	1.22	1.22	1.36
S4S-L	10-16x16	1.29	1.29	1.27
S2L-L	10-16x20	1.72	1.72	1.91
S2T-L	10-16x20	1.67	1.67	1.85
S4S-L	10-16x20	1.93	1.93	1.91
S2L-L	12-24x20	1.07	1.07	1.24
S2T-L	12-24x20	0.98	0.98	1.13
S4S-L	12-24x20	1.22	1.22	1.25
Mean		**1.32**	**1.32**	**1.41**
C.O.V.		**0.22**	**0.22**	**0.21**

See Equations (4-6) through (4-9) for Design Model 1, and Equations (4-10) through (4-14) for Design Model 2.

Table N.4 Daudet Data - Comparing Tested to Computed Strength

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
PN1-10T1-S1-1	1.24	1.24	1.40
PN1-10T1-S1-2	1.21	1.21	1.37
PN1-10T1-S1-3	1.27	1.27	1.44
PN2-10T1-S1-1	1.10	1.10	1.13
PN2-10T1-S1-2	1.23	1.23	1.26
PN2-10T1-S1-3	1.19	1.19	1.22
PN3-10T1-S1-1	1.13	1.13	1.07
PN3-10T1-S1-2	1.06	1.06	1.01
PN3-10T1-S1-3	1.07	1.07	1.02
PN1-12T1-S1-1	1.30	1.30	1.53
PN1-12T1-S1-2	1.18	1.18	1.40
PN1-12T1-S1-3	1.28	1.28	1.51
PN2-12T1-S1-1	1.45	1.45	1.54
PN2-12T1-S1-2	1.42	1.42	1.51
PN2-12T1-S1-3	1.31	1.31	1.39
PN3-12T1-S1-1	1.18	1.18	1.15
PN3-12T1-S1-2	1.19	1.19	1.17
PN3-12T1-S1-3	1.15	1.15	1.12
PN1-10T3-S1-1	1.15	1.15	1.30
PN1-10T3-S1-2	1.12	1.12	1.27
PN1-10T3-S1-3	1.00	1.00	1.14
PN2-10T3-S1-1	1.03	1.03	1.06
PN2-10T3-S1-2	0.99	0.99	1.02
PN2-10T3-S1-3	1.08	1.08	1.11
PN3-10T3-S1-1	1.01	1.01	0.96
PN3-10T3-S1-2	0.99	0.99	0.94
PN3-10T3-S1-3	0.98	0.98	0.93
PN1-12T3-S1-1	0.92	0.92	1.08
PN1-12T3-S1-2	0.96	0.96	1.13
PN1-12T3-S1-3	0.88	0.88	1.03
PN2-12T3-S1-1	1.05	1.05	1.12
PN2-12T3-S1-2	0.98	0.98	1.03

Test	**Model 1** P_{test}/P_{comp}	**Model 2** P_{test}/P_{comp}	**AISI** P_{test}/P_{comp}
PN2-12T3-S1-3	1.08	1.08	1.15
PN3-12T3-S1-1	0.99	0.99	0.97
PN3-12T3-S1-2	1.00	1.00	0.97
PN3-12T3-S1-3	0.91	0.91	0.89
PN1-25T3-S1-1	1.02	1.02	1.25
PN1-25T3-S1-2	1.02	1.02	1.26
PN1-25T3-S1-3	1.01	1.01	1.25
PN2-25T3-S1-1	0.93	0.93	1.03
PN2-25T3-S1-2	0.89	0.89	0.99
PN2-25T3-S1-3	0.93	0.93	1.02
PN3-25T3-S1-1	0.93	0.93	0.94
PN3-25T3-S1-2	0.96	0.96	0.97
PN3-25T3-S1-3	0.99	0.99	1.00
PN4-25T3-S1-1	1.02	1.02	0.96
PN4-25T3-S1-2	1.03	1.03	0.96
PN4-25T3-S1-3	1.03	1.03	0.96
TN1-10T1-S1-1	1.21	1.21	1.38
TN1-10T1-S1-2	1.27	1.27	1.44
TN1-10T1-S1-3	1.06	1.06	1.21
TN2-10T1-S1-1	1.13	1.13	1.16
TN2-10T1-S1-2	1.20	1.20	1.22
TN2-10T1-S1-3	1.18	1.18	1.21
TN3-10T1-S1-1	1.09	1.09	1.05
TN3-10T1-S1-2	1.10	1.10	1.05
TN3-10T1-S1-3	1.06	1.06	1.01
TN1-12T1-S1-1	1.39	1.39	1.65
TN1-12T1-S1-2	1.27	1.27	1.51
TN1-12T1-S1-3	1.24	1.24	1.46
TN2-12T1-S1-1	1.22	1.22	1.29
TN2-12T1-S1-2	1.29	1.29	1.36
TN2-12T1-S1-3	1.26	1.26	1.33
TN3-12T1-S1-1	1.15	1.15	1.13
TN3-12T1-S1-2	1.17	1.17	1.14
TN3-12T1-S1-3	1.16	1.16	1.14
TN1-10T3-S1-1	1.05	1.05	1.19
TN1-10T3-S1-2	1.13	1.13	1.28
TN1-10T3-S1-3	1.00	1.00	1.13
TN2-10T3-S1-1	1.07	1.07	1.09

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
TN2-10T3-S1-2	1.07	1.07	1.09
TN2-10T3-S1-3	0.98	0.98	1.00
TN3-10T3-S1-1	1.02	1.02	0.97
TN3-10T3-S1-2	0.98	0.98	0.93
TN3-10T3-S1-3	1.01	1.01	0.96
TN1-12T3-S1-1	0.91	0.91	1.08
TN1-12T3-S1-2	0.97	0.97	1.14
TN1-12T3-S1-3	0.88	0.88	1.04
TN2-12T3-S1-1	0.98	0.98	1.04
TN2-12T3-S1-2	1.02	1.02	1.08
TN2-12T3-S1-3	0.97	0.97	1.02
TN3-12T3-S1-1	1.04	1.04	1.02
TN3-12T3-S1-2	1.00	1.00	0.98
TN3-12T3-S1-3	0.94	0.94	0.93
TN1-25T3-S1-1	1.07	1.07	1.33
TN1-25T3-S1-2	1.04	1.04	1.29
TN1-25T3-S1-3	0.99	0.99	1.23
TN2-25T3-S1-1	0.91	0.91	1.00
TN2-25T3-S1-2	0.86	0.86	0.94
TN2-25T3-S1-3	0.84	0.84	0.93
TN3-25T3-S1-1	0.93	0.93	0.95
TN3-25T3-S1-2	0.92	0.92	0.94
TN3-25T3-S1-3	0.93	0.93	0.94
TN4-25T3-S1-1	0.93	0.93	0.88
TN4-25T3-S1-2	0.92	0.92	0.87
TN4-25T3-S1-3	0.92	0.92	0.87
278TN1-12T1-S2T-1	1.26	1.26	1.28
278TN1-12T1-S2T-2	1.25	1.25	1.27
278TN1-12T1-S2T-3	1.36	1.36	1.37
278TN2-12T1-S2T-1	1.46	1.46	1.33
278TN2-12T1-S2T-2	1.39	1.39	1.27
278TN2-12T1-S2T-3	1.40	1.40	1.28
278TN3-12T1-S2T-1	1.46	1.46	1.24
278TN3-12T1-S2T-2	1.44	1.44	1.23
278TN3-12T1-S2T-3	1.45	1.45	1.24
PN1-10T1-S2L-1	1.30	1.31	1.20
PN1-10T1-S2L-2	1.29	1.30	1.19
PN1-10T1-S2L-3	1.16	1.18	1.07

Test	Model 1 P_{test}/P_{comp}	Model 2 P_{test}/P_{comp}	AISI P_{test}/P_{comp}
PN2-10T1-S2L-1	1.25	1.27	1.05
PN2-10T1-S2L-2	1.39	1.40	1.16
PN2-10T1-S2L-3	1.22	1.24	1.02
PN3-10T1-S2L-1	1.20	1.21	0.93
PN3-10T1-S2L-2	1.20	1.21	0.92
PN3-10T1-S2L-3	1.17	1.19	0.91
PN1-12T1-S2L-1	1.46	1.46	1.49
PN1-12T1-S2L-2	1.52	1.52	1.55
PN1-12T1-S2L-3	1.43	1.43	1.46
PN2-12T1-S2L-1	1.36	1.36	1.25
PN2-12T1-S2L-2	1.38	1.38	1.27
PN2-12T1-S2L-3	1.39	1.39	1.28
PN3-12T1-S2L-1	1.31	1.31	1.11
PN3-12T1-S2L-2	1.24	1.24	1.05
PN3-12T1-S2L-3	1.10	1.10	0.93
PN1-12T1-S3L-1	1.38	1.38	1.32
PN1-12T1-S3L-2	1.36	1.36	1.29
PN1-12T1-S3L-3	1.43	1.43	1.36
PN2-12T1-S3L-1	1.30	1.30	1.12
PN2-12T1-S3L-2	1.32	1.32	1.13
PN2-12T1-S3L-3	1.30	1.30	1.12
PN3-12T1-S3L-1	1.30	1.30	1.02
PN3-12T1-S3L-2	1.30	1.30	1.02
PN3-12T1-S3L-3	1.33	1.33	1.05
278TN1-12T1-S4-1	1.36	1.36	1.22
278TN1-12T1-S4-2	1.41	1.41	1.27
278TN1-12T1-S4-3	1.41	1.41	1.26
278TN2-12T1-S4-1	1.20	1.20	0.97
278TN2-12T1-S4-2	1.23	1.23	1.00
278TN2-12T1-S4-3	1.25	1.25	1.01
278TN3-12T1-S4-1	1.31	1.31	1.00
278TN3-12T1-S4-2	1.36	1.36	1.03
278TN3-12T1-S4-3	1.31	1.31	0.99
Mean	**1.15**	**1.15**	**1.14**
C.O.V.	**0.15**	**0.15**	**0.15**

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