research report

Cold-Formed Steel Bolted Connections Using Oversized and Slotted Holes without Washers Phase 2

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Cold-Formed Steel Bolted Connections Using Oversized and Slotted Holes without Washers

- Phase 2 -

Final Research Report Submitted to

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by

Cheng Yu
Assistant Professor

Ke Xu
Graduate Research Assistant

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Department of Engineering Technology
University of North Texas
Denton, Texas 76207

ABSTRACT

In cold-formed steel (CFS) construction, bolted connections without washers for either oversized or slotted holes may significantly expedite the installation process and lower the cost. The North American Specification for the Design of Cold-Formed Steel Structural Members requires washers to be installed in bolted connections with oversized or slotted holes. A research project (Phase 1) sponsored by American Iron and Steel Institute was recently completed at the University of North Texas (UNT) that investigated the performance and strength of bolted CFS connections with oversized and slotted holes without using washers. The research presented in this report is the Phase 2 project in which the bolted CFS connections were studied in a broader respect in terms of the failure mechanism, the material thickness, and the hole configurations. Combined with Phase 1 results, the Phase 2 report gives a comprehensive evaluation of the behavior and strength of bolted CFS connections with oversized and slotted holes without using washers. Revisions to the existing AISI North American Specification requirements for bolted connections are proposed to account for the reduction in the connection strength caused by the oversized and slotted hole configurations without washers.

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1. BACKGROUND AND RESEARCH OBJECTIVES

1.1 BACKGROUND

The use of cold-formed steel (CFS) is an excellent alternative construction material for mid- and low-rise residential and commercial buildings. Light weight, high durability, high strength, and excellent material consistency are some of the reasons given for the increasing application of CFS in construction. The use of bolted connections is one of the common joining methods in CFS structures and it has been experimentally studied by a number of researchers. However, bolted connections using oversized or slotted holes without washers have not been fully studied yet, and that is the focus of this research effort.

The existing experimental results show four typical failure modes: Type I shear of the sheet, Type II bearing or piling up of material in front of the bolt, Type III tearing/rupture of the sheet in the net section, and Type IV shear in the bolt, usually occur in CFS bolted connections. Fig 1.1 illustrates these typical failure modes. This research focused on the first three failure modes of CFS bolted connections.

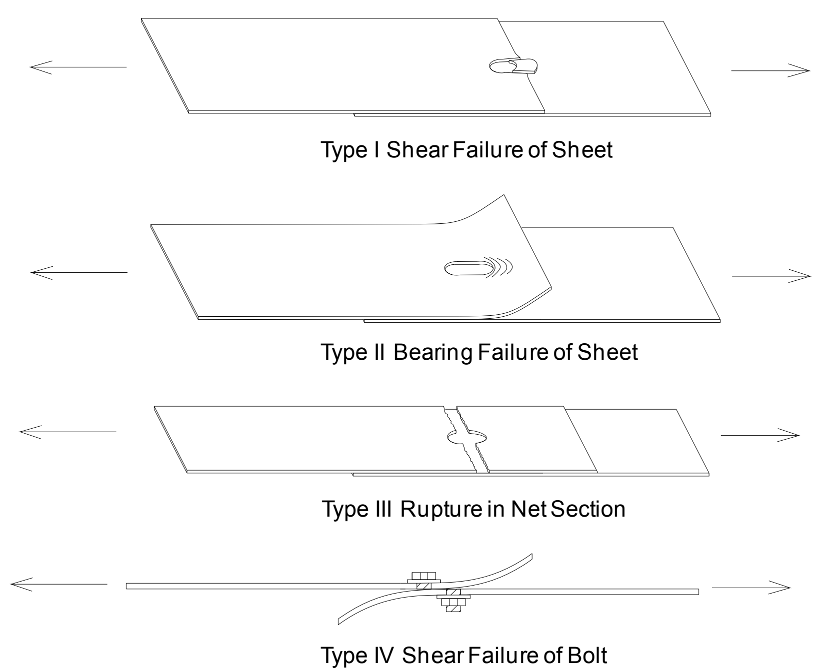

Fig 1.1 Typical Failures of Bolted CFS Connections

The current North American Specification for the Design of Cold-Formed Steel Structural Members (AISI S100, 2007) provides design provisions for these three of failure modes respectively. The hole dimensions together with the use of washers may significantly influence the strength of the bolted connections. The AISI S100 (2007) requires that "washers or backup plates should be used over oversized or short-slotted holes in an outer ply unless suitable performance is demonstrated by tests." A research project sponsored by the American Iron and Steel Institute (AISI) and the Metal Building Manufacturers Association (MBMA) was recently conducted by the authors to investigate the three failure modes of CFS bolted connections using oversized and slotted holes without washers.

The research project was divided into two phases. In Phase 1, the shear and the bearing failures of the sheets were studied by Yu (2008) and Yu and Sheerah (2008). In Phase 2, all three failure modes were investigated with a wider range of connection configurations compared with the Phase 1 work. The connection configurations in Phase 2 included (1) the sheet thickness varying from 30 mil to 118 mil; (2) the connection type – single and double shear; (3) the number of bolts – single and double bolts; -and (4) the diameter of the bolts – 1/4 in., 3/8 in., 1/2 in., 5/8 in.

This report provides test results of the Phase 2 work; it also includes the analyses on the entire test data set of both phases. Based on the comprehensive analyses, revision to the existing design provisions in the AISI S100 (2007) is proposed to account for the influences on the strength of bolted connections by the use of oversized or slotted holes without washers.

1.2 RESEARCH OBJECTIVES

The main research objectives are to experimentally investigate the behavior and strength of CFS bolted connections without washers when the steel sheets have oversized and/or slotted holes and to develop appropriate design equations for such connections if the existing design equations in the AISI S100 (2007) yield non-conservative predictions. Type I, II, and III failures of the specific bolted connections are addressed; the specific research objectives for Phase 2 are listed as follows.

1. Experimental investigation on the Type I, II, and III failures of CFS bolted connections using oversized holes or a combination of oversized holes with standard holes, AISI short-slot holes, or MBMA slotted holes without washers.
2. Examine the applicability of the AISI S100 (2007) design provisions for those three limit states. If necessary, new design provisions will be developed to accurately predict the nominal strength of CFS bolted connections using non-standard holes without washers.
3. Study the influence of the slot orientation (i.e. either parallel to or perpendicular to the direction of loading) to the strength of bolted connections.

2. LITERATURE REVIEW

2.1 DESIGN FOR SHEET SHEAR STRENGH

Experiments on bolted connections without washers for standard holes were conducted by a number of researchers (Yu 1982, Zadanfarrokh and Bryan 1992, LaBoube and Yu 1995, Wallace, Schuster, and LaBoube 2001a 2001b). It was found that the shear strength of the sheet, Type I failure, depends on the thinnest sheet thickness (t), the tensile strength of the controlling sheet (F_u), and the edge distance in the direction of the applied force (e). The AISI S100 (2007) adopts different formulae for the nominal shear strength for United States and Mexico, and Canada.

For United States and Mexico, the nominal shear strength per bolt (P_n) can be predicted by Equation 2-1 (Eq. E3.1-1 in Appendix A of AISI S100).

$$P_n = t\ e\ F_u \qquad (2\text{-}1)$$

where

e = distance from center of the hole to nearest edge of the adjacent hole or to end of the connected sheet

t = uncoated sheet thickness

F_u = tensile strength of sheet

For Canada, the nominal shear resistance per bolt as affected by edge distance for the typical connections illustrated in Fig 1.1 can be calculated by Equation 2-2 (Eq. C2.2-1 in Appendix B of AISI S100).

$$P_n = A_n\ F_u \qquad (2\text{-}2)$$

where

A_n = critical net area of connected part

= 0.6 e t

Definitions of F_u, e, t are same as listed for Equation 2-1.

It was found that a Type I failure is likely to occur when the connections have small e/d ratios (e/d < 2.5), where (d) is the bolt diameter. Equations 2-1 and 2-2 indicate that the influence of the presence of washers to the strength of Type I failures can be ignored in design, and the connection type (single shear or double shear) is not one of the controlling factors for the sheet shear strength affected by edge distance.

2.2 DESIGN FOR BEARING STRENGTH OF SHEETS

When the edge distance in the bolted connections is considerably large (e/d > 2.5), a bearing failure in the connected sheets may occur. Tests conducted previously (Winter 1956a and 1956b, Chong and Matlock 1974, Yu 1982, Zadanfarrokh and Bryan 1992, LaBoube and Yu 1995, Wallace, Schuster, and LaBoube 2001a) discovered that the sheet bearing strength primarily depended on the tensile strength of the sheet, the thickness of the thinner connected sheet, the ratio of bolt diameter to the sheet thickness (d/t) and the type of bearing connection (single or double shear, with or without washers, etc.) The presence of washers has significant impact on the bearing strength. The design method for the sheet bearing strength in AISI S100 (2007) was developed by Wallace, LaBoube, and Schuster (2001b) who analyzed experimental data from a total of 12 research projects.

The current design method in for bearing strength of bolted connections with standard holes is presented in Equation 2-3 (Eq. E3.3.1-1 of AISI S100 2007). The AISI S100 method uses a bearing factor, C, to account for the influence by the bolt diameter to sheet thickness ratio, d/t. A modification factor is used to reflect the washer option as well as the connection type (e.g. single shear or double shear). For single shear connections without a washer with standard holes, the modification factor equals 0.75, while a factor of 1.33 is used for the inside sheet of double shear connections without washers.

$P_n = m_f\ C\ d\ t\ F_u$ (2-3)

where

P_n = nominal bearing strength per bolt

m_f = modification factor, listed in Table 2-1

C = bearing factor, listed in Table 2-2

d = nominal bolt diameter

t = uncoated sheet thickness

F_u = tensile strength of sheet

Table 2-1 Modification Factor, m_f, for Bolted Connections with Oversized Holes (AISI S100 2007)

Type of bearing connection	m_f
Single shear and outside sheets of double shear connection with washers under both bolt head and nut	1.00
Single shear and outside sheets of double shear connection without washers under both bolt head and nut, or with only one washer	0.75
Inside sheet of double shear connection with or without washers	1.33

Table 2-2 Bearing Factor C, for Bolted Connections (AISI S100 2007)

Ratio of fastener diameter to member thickness, d/t	C
d/t<10	3
10≤d/t≤22	4-0.1(d/t)
d/t>22	1.8

It should be noted that the previous research found that the bearing failure in single shear connections and bearing failure in outside sheets of double shear connections had similar behavior and strength, therefore those two types of bearing are treated equally in the AISI S100 design method in terms of the nominal strength calculation and design factor values.

2.3 RUPTURE IN NET SECTION METHOD

Rupture in the net section is likely to happen when the edge distance is sufficiently large and the width of specimen is sufficiently small (d/s < 0.5). It was found that the nominal tensile strength of rupture in net section, Type III failure, of the single bolt connection illustrated in Fig 1.1 depends on the smallest net area of connected part (A_n) and the nominal tensile strength in the flat sheet (F_u). The AISI S100 (2007) adopts different formulae for the nominal tensile strength per bolt due to rupture in net section, P_n.

For United States and Mexico, P_n is calculated per Equation 2-4 (Eq. E3.2-1 in Appendix A of AISI S100 2007).

$$P_n = A_n F_t \tag{2-4}$$

where

P_n = nominal tensile strength of rupture in net section

A_n = net area of connected part

F_t = nominal tensile stress in flat sheet

When either washers are not provided under the bolt head and the nut, or only one washer is provided under either the bolt head or nut, for a single bolt, or a single row of bolts perpendicular to the force

$$F_t = (2.5\ d/s)\ F_u \leq F_u \tag{2-5}$$

d = nominal bolt diameter

s = sheet width divided by number of bolt holes in cross section being analyzed

F_u = tensile strength of sheet

For Canada, the nominal tensile resistance, T_n is calculated per Equation 2-6 (Eq. C2.2-1 in Appendix B of AISI S100 2007).

$$T_n = A_n F_u \tag{2-6}$$

where

A_n = critical net area of connected part

for failure normal to force due to direct tension, not involving stagger

$A_n = L_t\ t$, for failure normal to force due to direct tension, not involving stagger

F_u = tensile strength of sheet

3. TEST SETUP

3.1 TESTING EQUIPMENT AND METHOD FOR CONNECTION TESTS

The majority of the tension tests on CFS bolted connections in Phase 2 were conducted in a 20 kip capacity Instron 4482 universal testing machine which was also used for the Phase 1 tests. The deformation of the bolted connection was measured by an extensometer with a gauge length of 0.9843 in. Fig 3.1 shows test setup #1.

Fig 3.1 Setup #1 for Tension Tests on Bolted Connections

The top and the bottom grips shown in Fig 3.2 were made specifically to hold specimens up to 5 in. wide. Additional clamps were designed and used to guarantee that the specimens would not slip during testing by applying an extra clamping force.

Fig 3.2 Top and Bottom Grips – Setup #1

The tension tests were performed in a displacement control mode. The bottom grip was fixed to the base of the machine. The top grip connected to the crosshead of the machine, and the crosshead moved upwards at a constant speed of 0.2 in./minute during the test. The applied force, the displacement of the top grip, and the deformation of the bolted connection were recorded simultaneously by the Instron data acquisition system.

For the tests which had the estimated maximum load close to or greater than 20 kips, a structural frame with a 50 kip capacity hydraulic cylinder was used for the connection tests. Fig 3.3 shows test setup #2 adopted in this project. The specimens were bolted to the testing fixture, four bolts at each end. One position transducer was used to measure the connection deformation. Similar to setup #1, a constant speed was applied to the loading cylinder, a National Instruments data acquisition system was employed for test setup #2.

For all the bolted connections tested in this project, the bolts were all hand tightened and a torque wrench was used to monitor the applied torque not to exceed 40 lb-in.

Fig 3.3 Setup #2 for Tension Tests on Bolted Connections

3.2 TENSION COUPON TESTS FOR MATERIAL PROPERTIES

The material properties of the test specimens were obtained by tension coupon tests. The coupon tests were carried out in the same Instron 4482 universal testing machine used for the connection tests. The test protocol for the tension coupon tests was ASTM A370 Test Methods and Definitions for Mechanical Testing of Steel Products (2007). The coating on the coupons was removed prior to testing. For each material thickness from the same coil, four coupons were cut and tested, and the average values were reported in Section 5.1 of this report. The actual thickness and material properties were used in this research for data analyses.

4. TEST SPECIMENS OF PHASE 2

The Phase 2 work is a continuation of the Phase 1 research which studied the bearing and shear failure of the connected sheets in CFS bolted connections using oversized holes without washers. The Phase 2 continues to investigate those two types of failure by testing a broader range of connection configurations. In addition to the bearing and shear failures, the rupture of net section of the sheets is also part of the Phase 2 scope. The test parameters include:

- CFS sheet nominal thicknesses range from 27 mil to 114 mil with minimum specified yield stresses of 33 ksi and 50 ksi.
- Single shear and double shear connections with one bolt or two bolts.
- ASTM A307 bolts with diameters of 3/8 in., 1/2 in., and 5/8 in. SAE Grade 8 bolts with diameters of 1/2 in. and 5/8 in.
- Oversize hole, AISI short-slot hole, MBMA slotted holes.
- The slotted hole's orientation: parallel and perpendicular to the direction of the applied load.

The dimensions of the hole and slot dimensions investigated in this research phase are listed in Table 4-1.

Table 4-1 Dimensions of Oversize Holes and Slotted Holes for Phase 2 Tests

Nominal bolt diameter, d (in.)	AISI standard hole diameter, d_h (in.)	AISI oversized hole diameter, d_h (in.)	AISI short-slot hole dimensions (in.)	MBMA slotted hole dimensions (in.)
3/8	13/32	7/16	13/32 x 5/8	-
1/2	9/16	5/8	9/16 x 3/4	9/16 x 7/8
5/8	11/16	3/4	11/16 x 7/8	-

4.1 TEST MATRICES FOR INVESTIGATING BEARING AND SHEAR FAILURES IN SHEETS

The first task of Phase 2 tests is to continue the Phase 1 investigation on the shear failure and bearing failure in the connected sheets, the width of the specimens has to be sufficiently large to prevent rupture failure from occurring in the net section. Zadanfarrokh and Bryan (1992) recommended the width of connected sheet, $w = 6.25d$ for bearing tests with the nominal bolt diameter $d \geq 0.4$ in. Fig 4.1 shows the dimensions recommended by Zadanfarrokh and Bryan. Since the maximum bolt diameter in this research project is 5/8 in.,so w = 6.25 (5/8) = 3.9 in. and therefore the sheet width for the connections in the first task is set to 4 in.

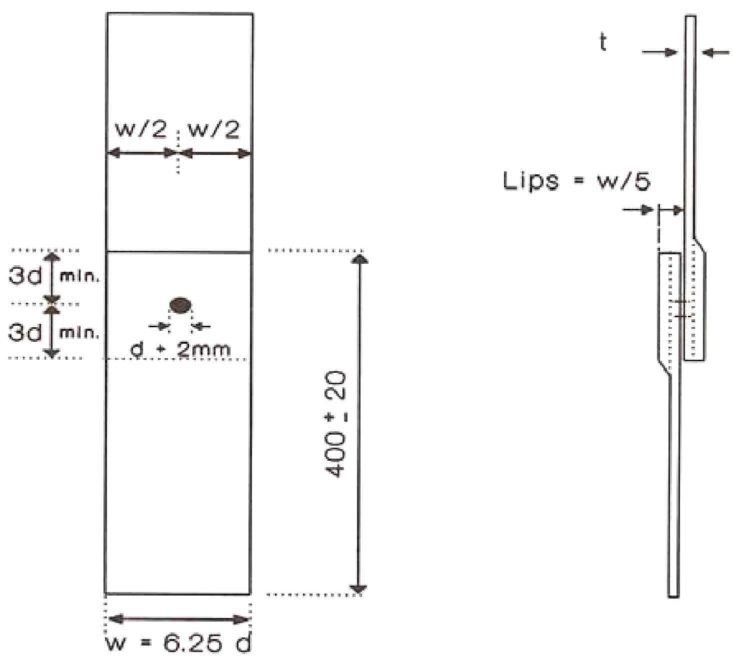

Fig 4.1 Recommended Test Dimensions for Structural Bolts (Zadanfarrokh and Bryan, 1992)

When the edge distance in the direction of the applied load is sufficiently small, the bolted connection may fail by shear of the sheet. Research done by Chong and Matlock (1975), Gilchrist and Chong (1979), and Yu (1982) indicated that e/d = 2.5 was approximately the breaking point to distinguish the sheet shear and sheet bearing failure modes. In Phase 2 tests, the connections with e/d value of 4 are tested to investigate the bearing failure. The sheet shear failure is investigated by testing connections with e/d = 1.5. The length of the connected sheets was 15 in. for all connections, which is based on the recommended value by Zadanfarrokh and Bryan (1992).

The sheet dimensions for the bearing and shear failure tests are shown in Figs 4.2 and 4.3 respectively for one-bolt connections and two-bolt connections. The distance between centers of bolt holes for the connections with two bolts is equal to three times the nominal bolt diameter, which meets the minimum spacing requirement in Section E3.1 of the AISI S100 (2007). The other notations in Figs 4.2 and 4.3 are defined as follows:

O – AISI oversize hole;

S – AISI standard hole;

SSL – AISI short slot parallel to loading direction;

SSLM –MBMA slot parallel to loading direction;

SST – AISI short slot perpendicular to the loading direction;

SSTM – MBMA slot perpendicular to the loading direction.

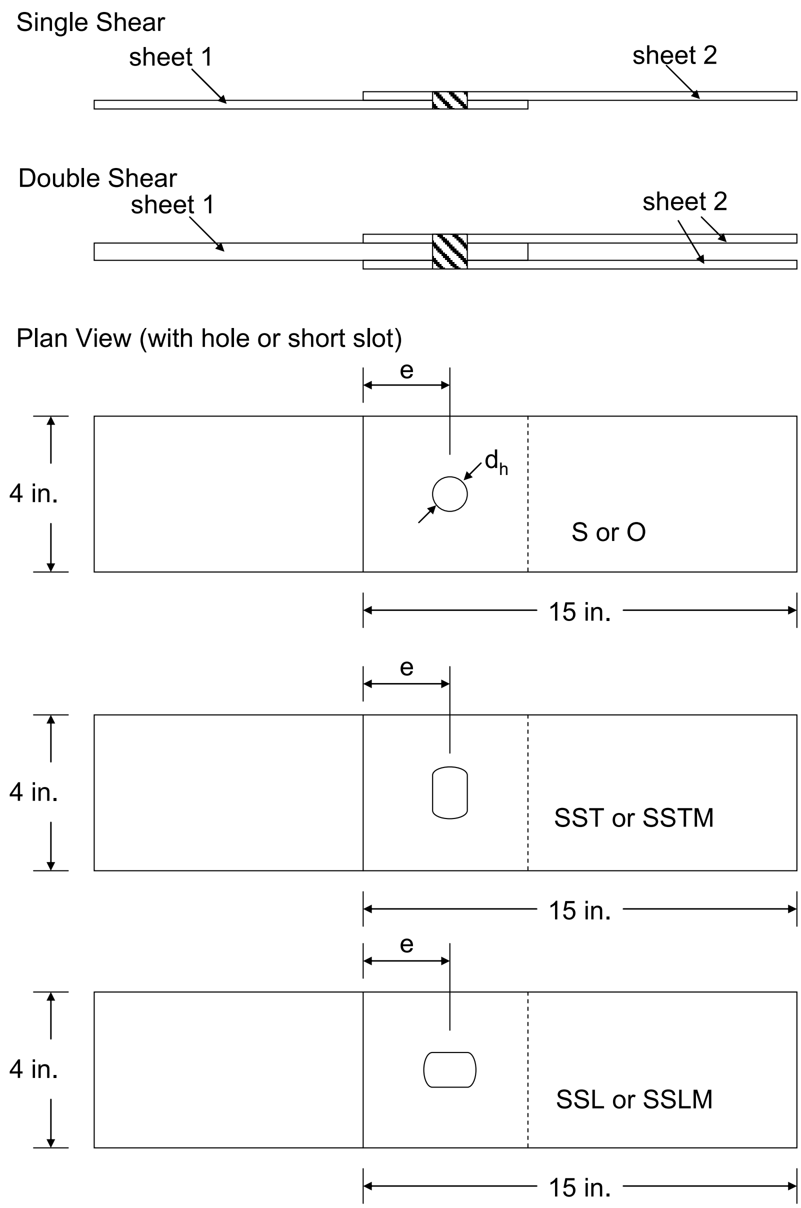

Fig 4.2 Dimensions of Specimens with One Bolt for Bearing and Shear Failure

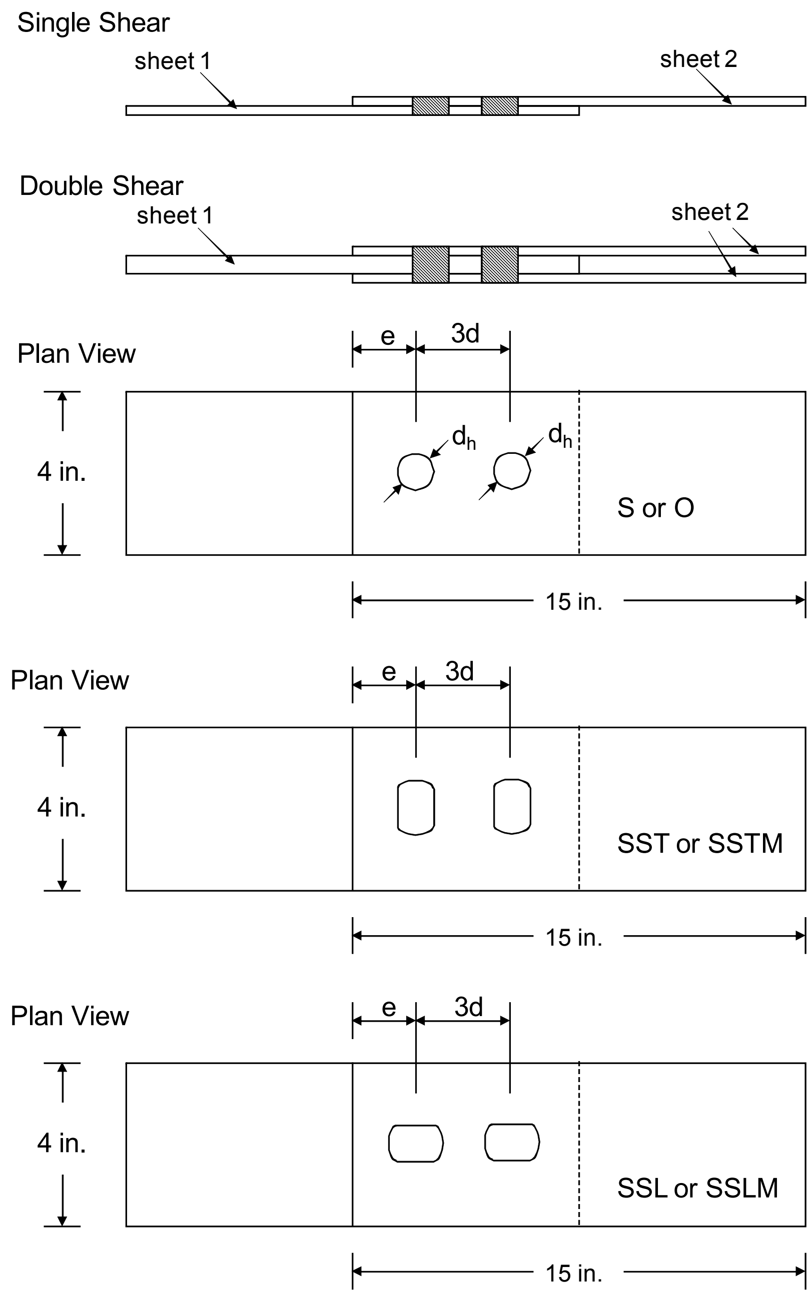

Fig 4.3 Dimensions of Specimens with Two Bolts for Bearing and Shear Failure

The specimen configurations in Phase 2 for bearing and sheet shear failures are listed in Tables 4-2 through 4-4. For each specimen configuration, two identical tests are conducted. If the difference of the first two tests is greater than 15% of the average result, a third test would be performed.

Table 4-2 Phase 2 Test Matrix for Connections with Oversize Holes

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel ductility[1]	Bolt diameter d (in.)	No. of bolts	Connection type[2]	Hole config.[3]	e/d	No. of config.
1	105	105	H	5/8	1	S	O/O	1.5,4	2
2	90	90	H	5/8	1	S	O/O	1.5,4	2
3	75	75	H	5/8	1	S	O/O	1.5,4	2
4	105	105	H	1/2	1	S	O/O	1.5,4	2
5	90	90	H	1/2	1	S	O/O	1.5,4	2
6	75	75	H	1/2	1	S	O/O	1.5,4	2
7	60	60	H	1/2	1	S	O/O	1.5,4	2
8	105	105	H	1/2	2	S	O/O	4	1
9	90	90	H	1/2	2	S	O/O	4	1
10	75	75	H	1/2	2	S	O/O	4	1
11	60	60	H	1/2	2	S	O/O	4	1
12	43	43	H	3/8	1	S	O/O	1.5,4	2
13	33	33	H	3/8	1	S	O/O	1.5,4	2
14	60	43	H	1/2	1	D	O/O	1.5,4	2
14	60	60	H	1/2	1	D	O/O	1.5,4	2
15	75	43	H	1/2	1	D	O/O	1.5,4	2
16	75	75	H	1/2	1	D	O/O	1.5,4	2
17	90	60	H	1/2	1	D	O/O	1.5,4	2
18	90	90	H	1/2	1	D	O/O	1.5,4	2
19	105	60	H	1/2	1	D	O/O	1.5,4	2
20	105	105	H	1/2	1	D	O/O	1.5,4	2
21	43	33	H	3/8	1	D	O/O	1.5,4	2
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10$. 2: S --- single shear; D --- double shear. 3: O --- oversize hole.								Total	40 config. / 80 tests

Table 4-3 Phase 2 Test Matrix for Connections with Standard Holes

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel ductility[1]	Bolt diameter d (in.)	No. of bolts	Connection type[2]	Hole config.[3]	e/d	No. of config.
1	105	105	H	5/8	1	S	O/S	1.5,4	2
2	90	90	H	5/8	1	S	O/S	1.5,4	2
3	75	75	H	5/8	1	S	O/S	1.5,4	2
4	105	105	H	1/2	1	S	O/S	1.5,4	2
5	90	90	H	1/2	1	S	O/S	1.5,4	2
6	75	75	H	1/2	1	S	O/S	1.5,4	2
7	60	60	H	1/2	1	S	O/S	1.5,4	2
8	105	105	H	1/2	2	S	O/S	4	1
9	90	90	H	1/2	2	S	O/S	4	1
10	75	75	H	1/2	2	S	O/S	4	1
11	60	60	H	1/2	2	S	O/S	4	1
12	43	43	H	3/8	1	S	O/S	1.5,4	2
13	33	33	H	3/8	1	S	O/S	1.5,4	2
14	60	43	H	1/2	1	D	O/S	1.5,4	2
14	60	60	H	1/2	1	D	O/S	1.5,4	2
15	75	43	H	1/2	1	D	O/S	1.5,4	2
16	75	75	H	1/2	1	D	O/S	1.5,4	2
17	90	60	H	1/2	1	D	O/S	1.5,4	2
18	90	90	H	1/2	1	D	O/S	1.5,4	2
19	105	60	H	1/2	1	D	O/S	1.5,4	2
20	105	105	H	1/2	1	D	O/S	1.5,4	2
21	43	27	H	3/8	1	D	O/S	1.5	1
22	43	33	H	3/8	1	D	O/S	4	1
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10\%$). 2: S --- single shear; D --- double shear. 3: S --- standard hole.								Total	40 config. / 80 tests

Table 4-4 Phase 2 Test Matrix for Connections with Slots

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel ductility[1]	Bolt diameter d (in.)	No. of bolts	Connection type[2]	Hole config.[3]	e/d	No. of config.
1	105	105	H	5/8	1	S	O/SSL	1.5,4	2
2	90	90	H	5/8	1	S	O/SSL	1.5,4	2
3	75	75	H	5/8	1	S	O/SSL	1.5,4	2
4	105	105	H	5/8	1	S	O/SST	1.5,4	2
5	90	90	H	5/8	1	S	O/SST	1.5,4	2
6	75	75	H	5/8	1	S	O/SST	1.5,4	2
7	105	105	H	1/2	1	S	O/SSL	1.5,4	2
8	90	90	H	1/2	1	S	O/SSL	1.5,4	2
9	75	75	H	1/2	1	S	O/SSL	1.5,4	2
10	60	60	H	1/2	1	S	O/SSL	1.5,4	2
11	105	105	H	1/2	1	S	O/SSLM	1.5,4	2
12	90	90	H	1/2	1	S	O/SSLM	1.5,4	2
13	75	75	H	1/2	1	S	O/SSLM	1.5,4	2
14	60	60	H	1/2	1	S	O/SSLM	1.5,4	2
14	105	105	H	1/2	1	S	O/SST	1.5,4	2
15	90	90	H	1/2	1	S	O/SST	1.5,4	2
16	75	75	H	1/2	1	S	O/SST	1.5,4	2
17	60	60	H	1/2	1	S	O/SST	1.5,4	2
18	105	105	H	1/2	1	S	O/SSTM	1.5,4	2
19	90	90	H	1/2	1	S	O/SSTM	1.5,4	2
20	75	75	H	1/2	1	S	O/SSTM	1.5,4	2
21	60	60	H	1/2	1	S	O/SSTM	1.5,4	2
22	105	105	H	1/2	2	S	O/SSL	4	1
23	90	90	H	1/2	2	S	O/SSL	4	1
24	75	75	H	1/2	2	S	O/SSL	4	1
25	60	60	H	1/2	2	S	O/SSL	4	1
26	105	105	H	1/2	2	S	O/SSLM	4	1
27	90	90	H	1/2	2	S	O/SSLM	4	1
28	75	75	H	1/2	2	S	O/SSLM	4	1
29	60	60	H	1/2	2	S	O/SSLM	4	1
30	105	105	H	1/2	2	S	O/SST	4	1
31	90	90	H	1/2	2	S	O/SST	4	1
32	75	75	H	1/2	2	S	O/SST	4	1
33	60	60	H	1/2	2	S	O/SST	4	1
34	105	105	H	1/2	2	S	O/SSTM	4	1
35	90	90	H	1/2	2	S	O/SSTM	4	1
36	75	75	H	1/2	2	S	O/SSTM	4	1
37	60	60	H	1/2	2	S	O/SSTM	4	1
38	43	43	H	3/8	1	S	O/SSL	1.5,4	2
39	43	43	H	3/8	1	S	O/SST	1.5,4	2
40	33	33	H	3/8	1	S	O/SST	4	1

Table 4-4 Phase 2 Test Matrix for Connections with Slots (Continued)

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel ductility[1]	Bolt diameter d (in.)	No. of bolts	Connection type[2]	Hole config.[3]	e/d	No. of config.
41	27	27	H	3/8	1	S	O/SSL	1.5	1
42	27	27	H	3/8	1	S	O/SST	1.5	1
43	27	27	H	3/8	1	S	O/SST	4	1
44	60	43	H	1/2	1	D	O/SSL	1.5,4	2
45	60	60	H	1/2	1	D	O/SSL	1.5,4	2
46	75	43	H	1/2	1	D	O/SSL	1.5,4	2
47	75	75	H	1/2	1	D	O/SSL	1.5,4	2
48	90	60	H	1/2	1	D	O/SSL	1.5,4	2
49	90	90	H	1/2	1	D	O/SSL	1.5,4	2
50	105	60	H	1/2	1	D	O/SSL	1.5,4	2
51	105	105	H	1/2	1	D	O/SSL	1.5,4	2
52	60	43	H	1/2	1	D	O/SSLM	1.5,4	2
53	60	60	H	1/2	1	D	O/SSLM	1.5,4	2
54	75	43	H	1/2	1	D	O/SSLM	1.5,4	2
55	75	75	H	1/2	1	D	O/SSLM	1.5,4	2
56	90	60	H	1/2	1	D	O/SSLM	1.5,4	2
57	90	90	H	1/2	1	D	O/SSLM	1.5,4	2
58	105	60	H	1/2	1	D	O/SSLM	1.5,4	2
59	105	105	H	1/2	1	D	O/SSLM	1.5,4	2
60	60	43	H	1/2	1	D	O/SST	1.5,4	2
61	60	60	H	1/2	1	D	O/SST	1.5,4	2
62	75	43	H	1/2	1	D	O/SST	1.5,4	2
63	75	75	H	1/2	1	D	O/SST	1.5,4	2
64	90	60	H	1/2	1	D	O/SST	1.5,4	2
65	90	90	H	1/2	1	D	O/SST	1.5,4	2
66	105	60	H	1/2	1	D	O/SST	1.5,4	2
67	105	105	H	1/2	1	D	O/SST	1.5,4	2
68	60	43	H	1/2	1	D	O/SSTM	1.5,4	2
69	60	60	H	1/2	1	D	O/SSTM	1.5,4	2
70	75	43	H	1/2	1	D	O/SSTM	1.5,4	2
71	75	75	H	1/2	1	D	O/SSTM	1.5,4	2
72	90	60	H	1/2	1	D	O/SSTM	1.5,4	2
73	90	90	H	1/2	1	D	O/SSTM	1.5,4	2
74	105	60	H	1/2	1	D	O/SSTM	1.5,4	2
75	105	105	H	1/2	1	D	O/SSTM	1.5,4	2
76	43	33	H	3/8	1	D	O/SSL	1.5	1
77	43	33	H	3/8	1	D	O/SST	1.5,4	2
78	43	27	H	3/8	1	D	O/SSL	4	1
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10\%$). 2: S --- single shear; D --- double shear. 3: SSL or SSLM – AISI or MBMA slot parallel to loading direction; SST or SSTM – AISI or MBMA slot perpendicular to loading direction.								Total	136 config. 272 tests

4.2 TEST MATRICES FOR INVESTIGATING RUPTURE IN NET SECTION OF SHEETS

The second task of the Phase 2 research is to investigate the rupture in the net section of bolted connections using oversized and/or slotted holes without washers. In order to ensure the occurrence of rupture in net section, the width of the connected sheets should be sufficiently small. Test results by Chong and Matlock (1975) indicated that when the bolt diameter-to-sheet width ratio d/s was less than 0.5, rupture in the net section was likely to occur. The ratios of d/s for this group of specimens are therefore chosen to be 0.2 or 0.4. At the same time the edge distance in the loading direction, e, should be sufficiently large to prevent shear failure in the connected sheet. Zadanfarrokh and Bryan (1992) recommended a minimum e = 3d to restrict sheet shear failure. Since the maximum bolt diameter in this research is 5/8 in., the edge distance, e, is set to 3 in. for all the specimens in the second task of the Phase 2 research. Fig 4.4 shows the typical sheet dimensions for specimens for investigating the net section rupture.

Table 4-5 summarizes the test matrix for the study of the rupture failure limit state with an initial series of 24 tests. Additional tests would be conducted if the initial tests gave unexpected results. For all specimen configurations, two identical tests are conducted. If the difference of the peak load between the first two tests is greater than 15% of the average result, a third test would be performed.

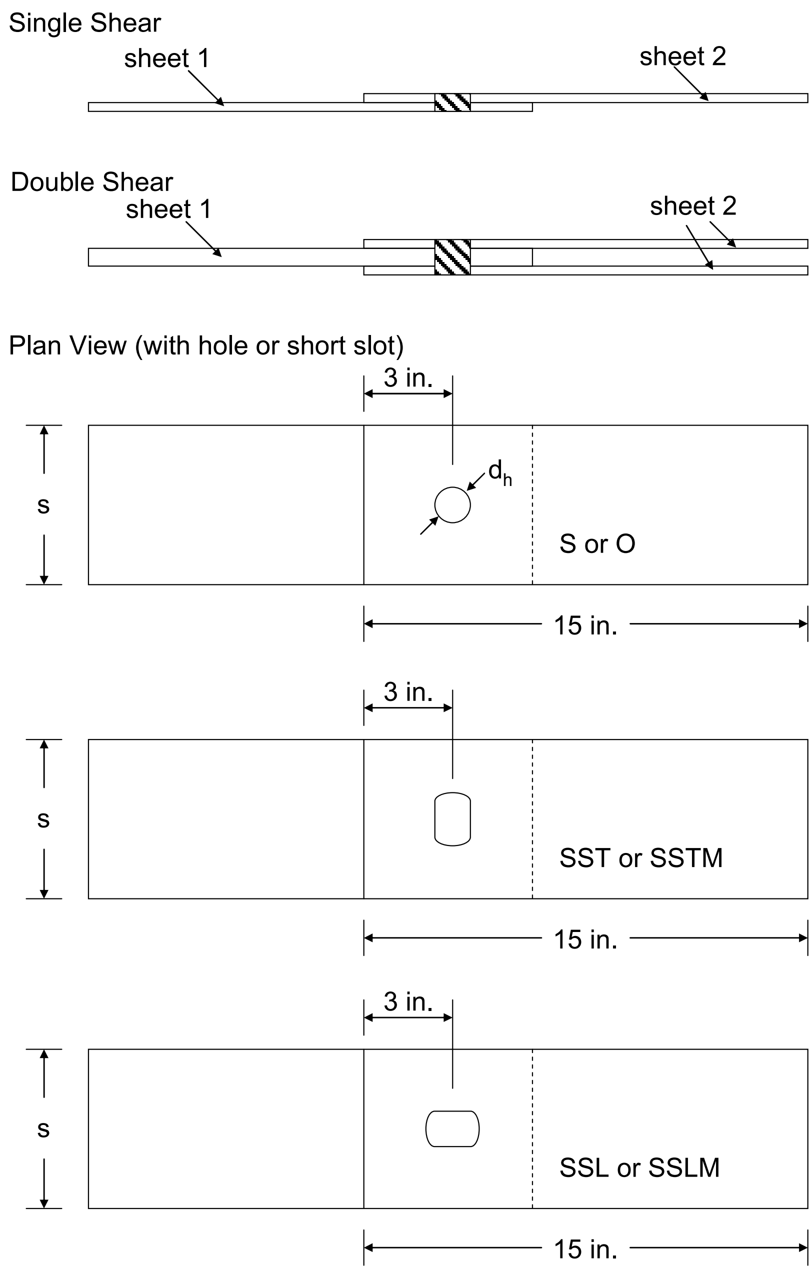

Fig 4.4 Dimensions of Specimens with One Bolt for Rupture in Net Section

Table 4-5 Phase 2 Test Matrix for Rupture in Net Section

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel ductility[1]	Bolt diameter d (in.)	No. of bolts	Connection type[2]	Hole config.[3]	d/s	No. of config.
1	75	75	H	1/2	1	S	O/O	0.2, 0.4	2
2	75	75	H	1/2	1	S	O/S	0.2, 0.4	2
3	75	75	H	1/2	1	S	O/SSL	0.2, 0.4	2
4	75	75	H	1/2	1	S	O/SSLM	0.2, 0.4	2
5	75	75	H	1/2	1	S	O/SST	0.2, 0.4	2
6	75	75	H	1/2	1	S	O/SSTM	0.2, 0.4	2
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10\%$). 2: S --- single shear; D --- double shear. 3: SSL or SSLM - AISI or MBMA slot parallel to loading direction; SST or SSTM - AISI or MBMA slot perpendicular to loading direction.								Total	12 config. 24 tests

4.3 SPECIMEN LABELING

The Phase 2 specimens were labeled according to the format illustrated in Figs 4.5 and 4.6 respectively for bearing or sheet shear failure tests and for net section rupture tests.

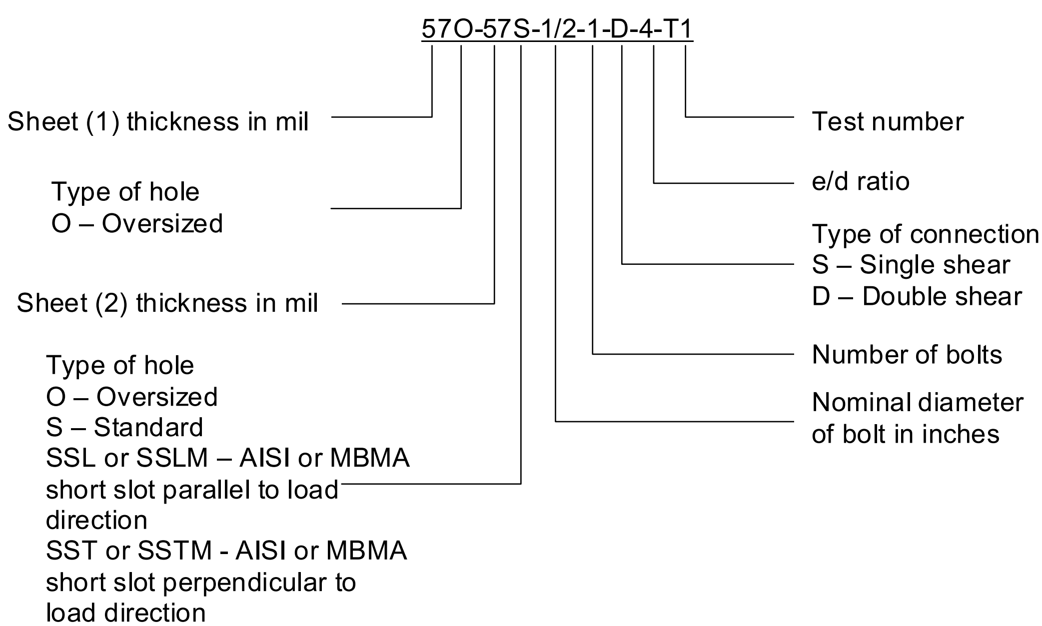

Fig 4.5 Specimen Labeling for Sheet Bearing and Shear Specimens

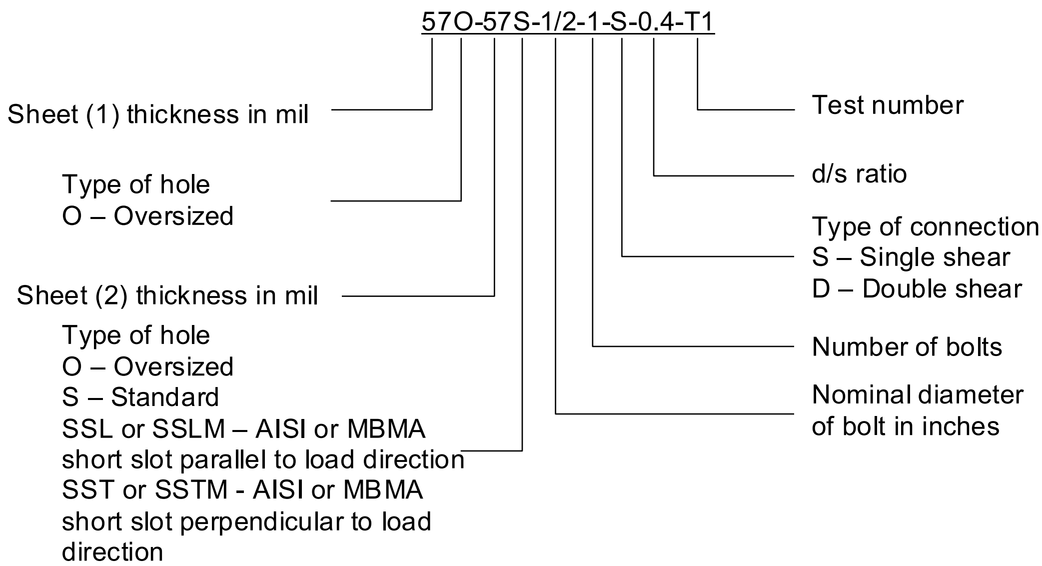

Fig 4.6 Specimen Labeling for Rupture in Net Section Specimens

5. TEST RESULTS

5.1 TENSION COUPON TESTS FOR MATERIAL PROPERTIES

Table 5-1 gives the experimentally determined material properties of each steel sheet thickness. Four tension coupon tests were conducted on each sheet thickness. The yield stress, F_y, was determined by the 0.2% offset method. The average values are provided in Table 5-1. Fig 5.1 shows the stress vs. strain curve of some steel sheet thicknesses. It is found that all of the high ductile steels used in Phase 2 meet the minimum requirements for material ductility specified by AISI S100 (2007). The current specification requires that the ratio of actual tensile strength to yield stress shall not be less than 1.08, and the total elongation shall not be less than 10% measured over a two-inch gage length.

The 43 mil (A) and 43 mil (B) sheets used in Phase 2 are from two different sources and therefore have different material properties. The actual thickness and material properties are used in the analyses of this research for calculating the nominal strength of bolted connections.

Table 5-1 Material Properties of Phase 2 Specimens

Nominal sheet thickness	Measured uncoated thickness (in.)	Actual F_y (ksi)	Actual F_u (ksi)	F_u/F_y	Elongation on 2-in. gage length	Ductility
27 mil	0.0240	50.3	57.8	1.15	21%	High
30 mil	0.0294	52.7	60.2	1.14	25%	High
43 mil (A)	0.0437	66.0	79.6	1.20	22%	High
43 mil (B)	0.0442	56.6	72.8	1.29	27%	High
57mil	0.0588	62.8	74.2	1.18	20%	High
73 mil	0.0760	63.6	74.1	1.16	12%	High
94 mil	0.0971	75.3	87.3	1.16	15%	High
114 mil	0.1217	65.7	73.1	1.11	12%	High

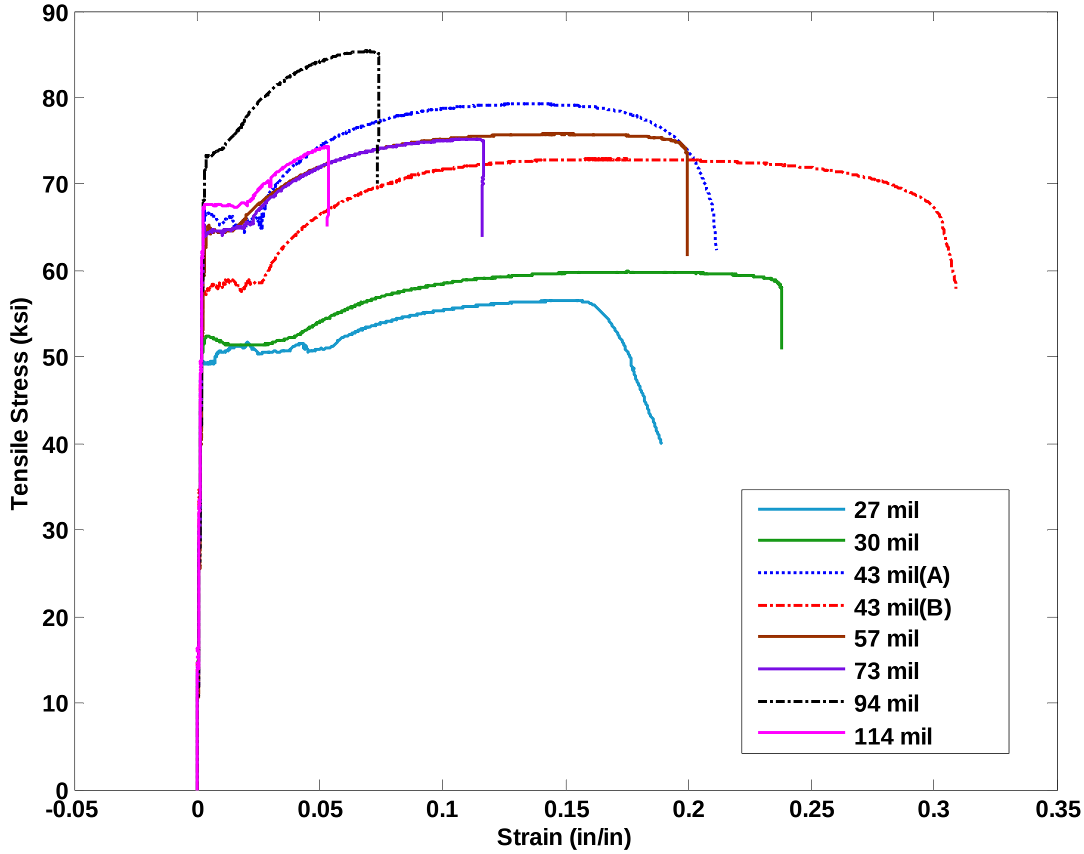

Fig 5.1 Stress – Strain Curves for Tested Materials

5.2 BEARING FAILURE OF SHEET

5.2.1 Bearing Failure of Connections with Oversized Holes

The bearing failure of bolted connections with oversized holes on all connected sheets was investigated by tension tests on specimens with e/d = 4. The test results are summarized in the Appendix Tables A-1 through A-4, where P_{test} is the recorded peak load per bolt, and Δ is the connection deformation at the peak load. The material properties of the sheets in the tables are the results from the tension coupon tests.

Due to the dimension of oversized holes, the tested bolted connections using 1/2 in. or larger diameter bolts may demonstrate up to 1/4 in. slippage before the connections start to bear loads. The initial slippage for connections with 1/4 in. bolt may go up to 1/8 in. The slippage distance is a random variable and it depends on the initial position of the bolt relative to the holes in the connected sheets. In order to avoid any influence by the unpredictable magnitude of bolt slippage, the bolt deformation that is being reported is the measurement from the initial contact of the bolts and the bearing surface of all connected sheets.

In the tests on single shear connections, the sheet material built up at the bearing area, the end portion of the connected sheets curled outwards, the bolt tilted and part of the bolt head and nut went through the sheet due to the significantly enlarged hole. Fig 5.2 shows the experimental load-deformation curves for the 94 mil single shear connections with a 5/8 in. diameter bolt. Fig 5.3 shows one of the failed 94 mil connection specimens after test.

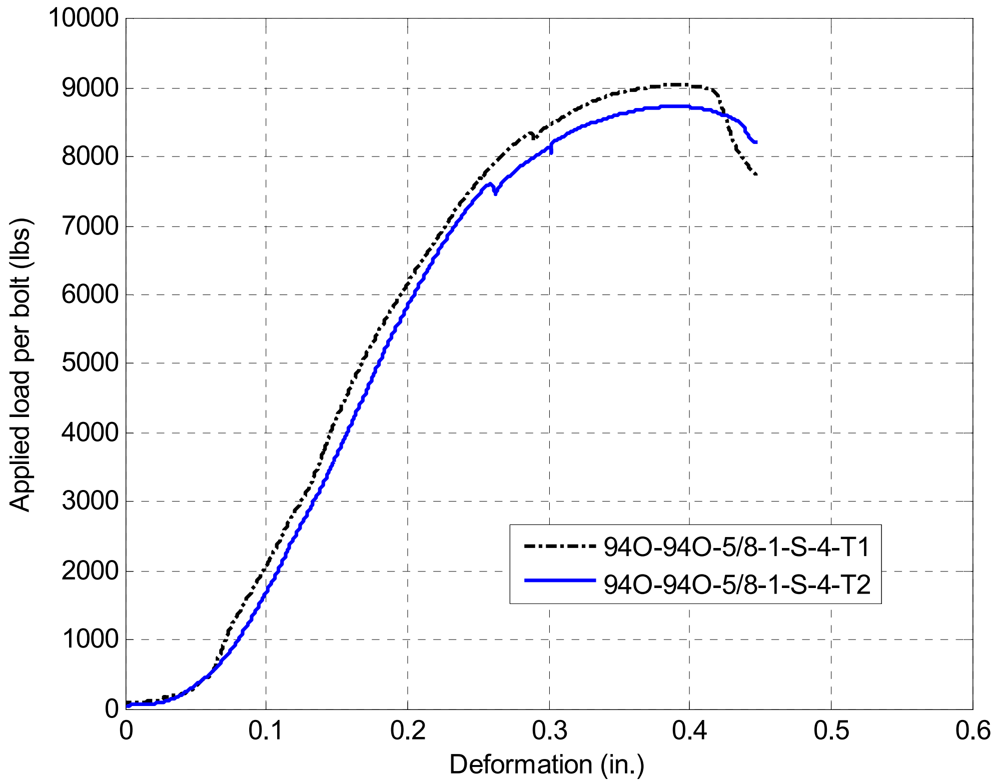

Fig 5.2 Load vs. Deformation Curves for 94 mil Single Shear Connections in Bearing

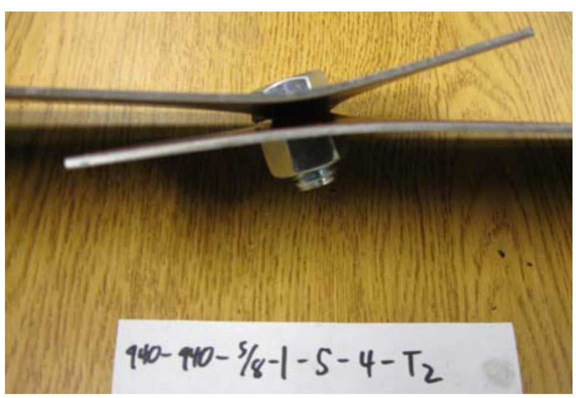

Fig 5.3 Sheet Bearing Failure of Test Specimen 94O-94O-5/8-1-S-4-T2

In the tests on double shear connections, two failure modes were observed: (1) bearing in the outside sheets; (2) bearing in the inside sheet. The test results for the two failure types are listed in the Appendix Tables A-3 and A-4. Fig 5.4 shows the bearing failure in the 57 mil outside sheets of a double shear connection using 94 mil steel for the inside sheet. The two outside sheets warped and the bolt holes were significantly enlarged causing material built up and cracking on the bearing. Unlike single shear connections, the bolt in double shear connections remained perpendicular to the loading direction in the tests. Fig 5.5 illustrates the experimental load-deformation curves for the double shear connections shown in Fig 5.4.

Fig 5.4 Sheet Bearing Failure of Test Specimen 94O-57O-1/2-1-D-4-T1

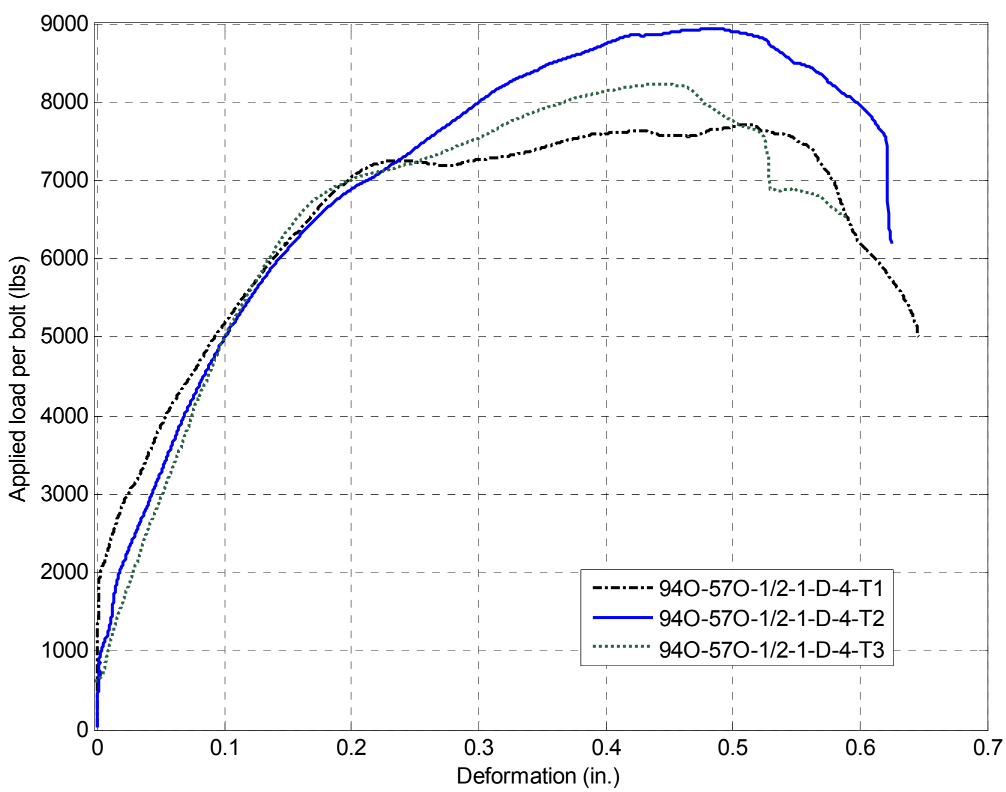

Fig 5.5 Load vs. Deformation Curves for Double Shear Connections with Oversized Holes

For double shear connections with the same inner and outer sheet thickness, the bearing failure always occurred in the inside sheet. Figs 5.6 and 5.7 respectively show the experimental load-deformation curves and failure mode for a double shear connection failed in the inside sheet. The bolt remained perpendicular to the sheets in the test, and no failure was observed in the two outside sheets which were able to remain straight.

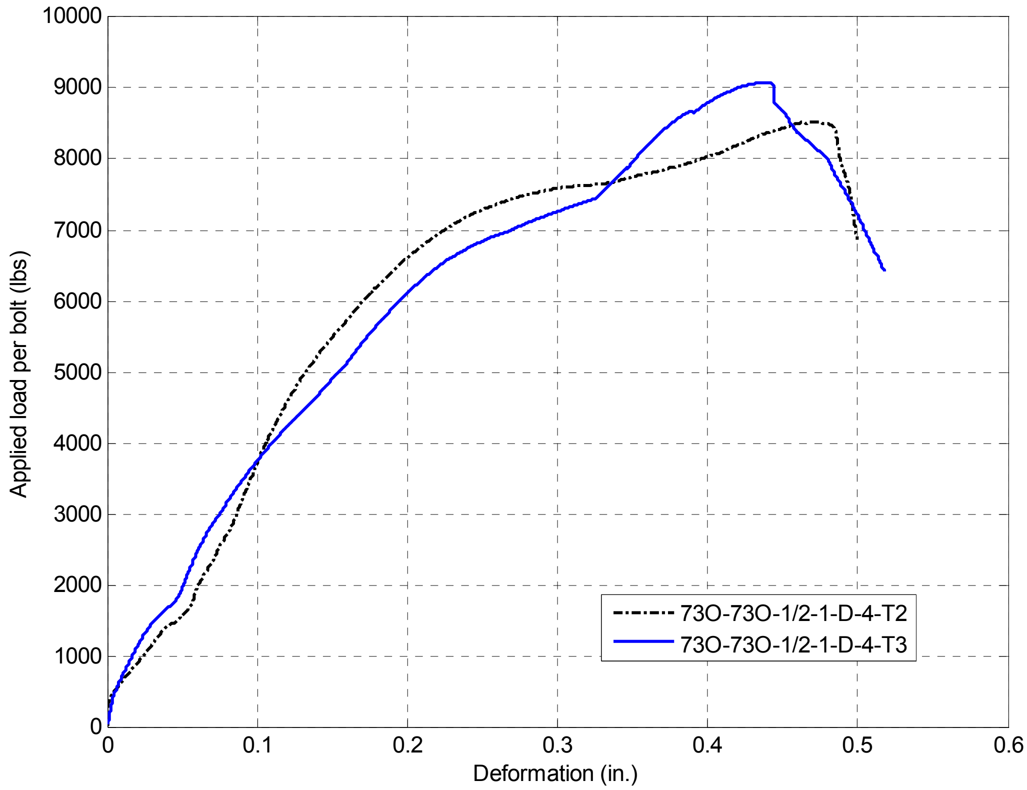

Fig 5.6 Load vs. Deformation Curves for 73 mil Double Shear Connections

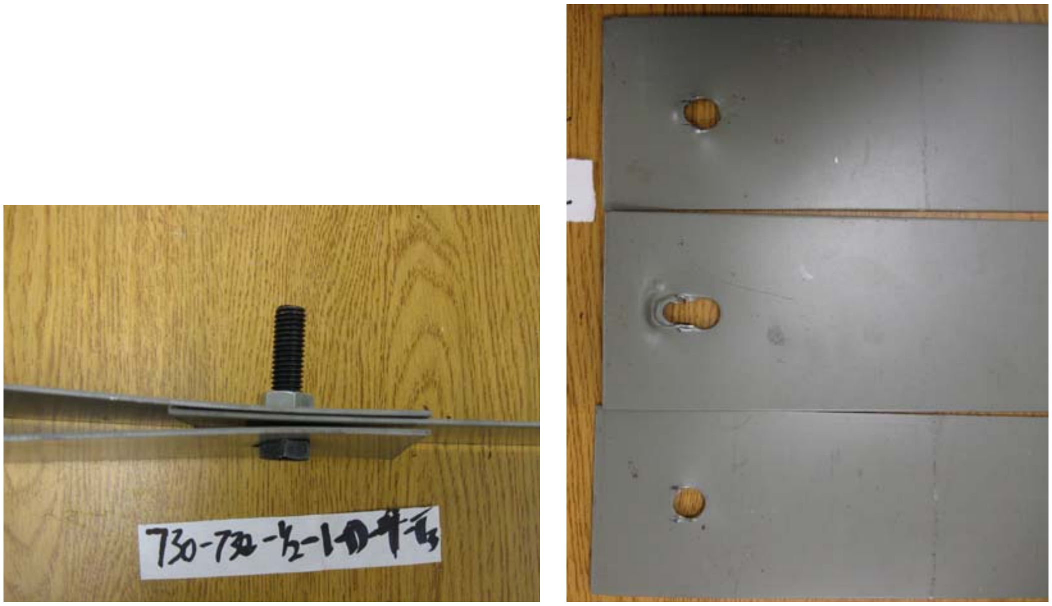

Fig 5.7 Bearing Failure of Test Specimen 73O-73O-1/2-1-D-4-T3

5.2.2 Bearing Failure of Connections with Oversized and Standard Holes

The bearing failure of connections using oversized and standard holes on different connected sheets was investigated. Both single shear and double shear configurations were tested. For the double shear connections, the oversized hole was in the inside sheet. The test results for the combined oversized and standard hole configurations are listed in the Appendix Tables A-5 through A-8.

For single shear connections, both sheets distorted, and holes in both sheets were enlarged to allow rotation of the bolt. Fig 5.8 is a comparison between 114 mil single shear connections with different hole configurations. Both tests yielded similar behavior and reached the peak loads at similar deformation amount. Fig 5.9 shows the failed 114 mil connection with an oversized hole in one sheet and a standard hole in the other sheet.

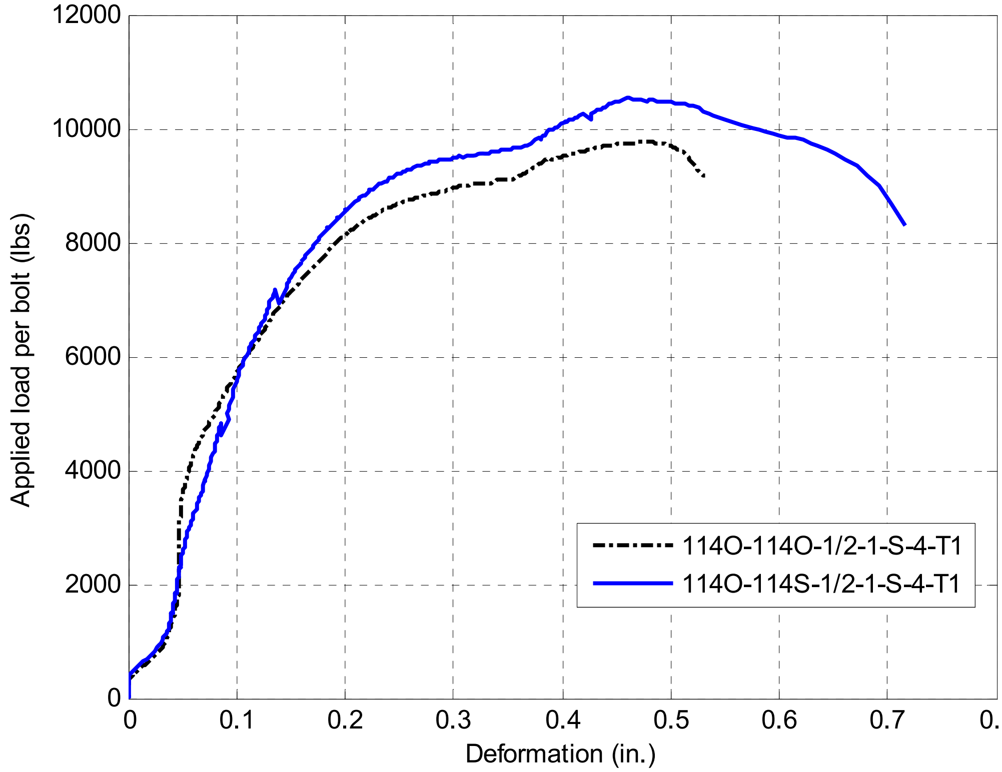

Fig 5.8 Comparison of Tests on 114 mil Single Shear Connections

Fig 5.9 Bearing Failure of Test Specimen 114O-114S-1/2-1-S-4-T1

For double shear connections, two bearing failure types occurred. When a higher strength sheet is used for the inside sheet, the two outer sheets may fail in bearing. Fig 5.10 shows a bearing failure in the 57 mil outside sheets of a connection using a 94 mil inside sheet. Standard holes were punched in the two outside sheets while the inside sheet used an oversized hole.

Fig 5.10 Bearing Failure of Test Specimen 94O-57S-1/2-1-D-4-T2

Fig 5.11 shows a bearing failure in a 94 mil inside sheet of a double shear connection using the same material for both inside and outside sheets.

Fig 5.11 Bearing Failure of Test Specimen 94O-94S-1/2-1-D-4-T2

5.2.3 Bearing Failure of Connections with Oversized and Slotted Holes

The CFS bolted connections using combined oversized and slotted hole configurations were investigated in Phase 2. For single shear connections, the two connected sheets had different holes in each sheet. For double shear connections, the inside sheet used an oversized hole and the two outside sheets used slotted holes. Two types of slotted holes were studied: AISI short-slot holes and MBMA slotted holes. The hole dimensions are specified in Table 4-1. The slotted holes were oriented in two ways: parallel or perpendicular to the applied load.

The test results for bearing failure of connections using oversized and slotted holes are summarized in the Appendix Tables A-9 through A-12. Fig 5.12 shows the failure mode of a 114 mil single shear connection with an oversized hole in one sheet and a SSLM slot in the other sheet. The bolt tilted and portions of the head and nut passed through the holes which resulted in separation of the two sheets. Fig 5.13 compares the load vs. deformation curves of 114 mil connections with an oversized hole and SSL or SSLM slot. SSLM slots are longer than SSL slots, therefore more rotation of the bolts can be observed when SSLM slots are used.

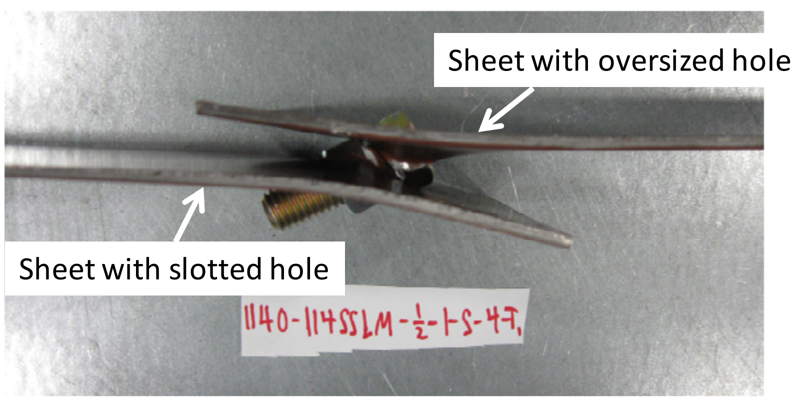

Fig 5.12 Bearing Failure of Test Specimen 114O-114SSLM-1/2-1-S-4-T1

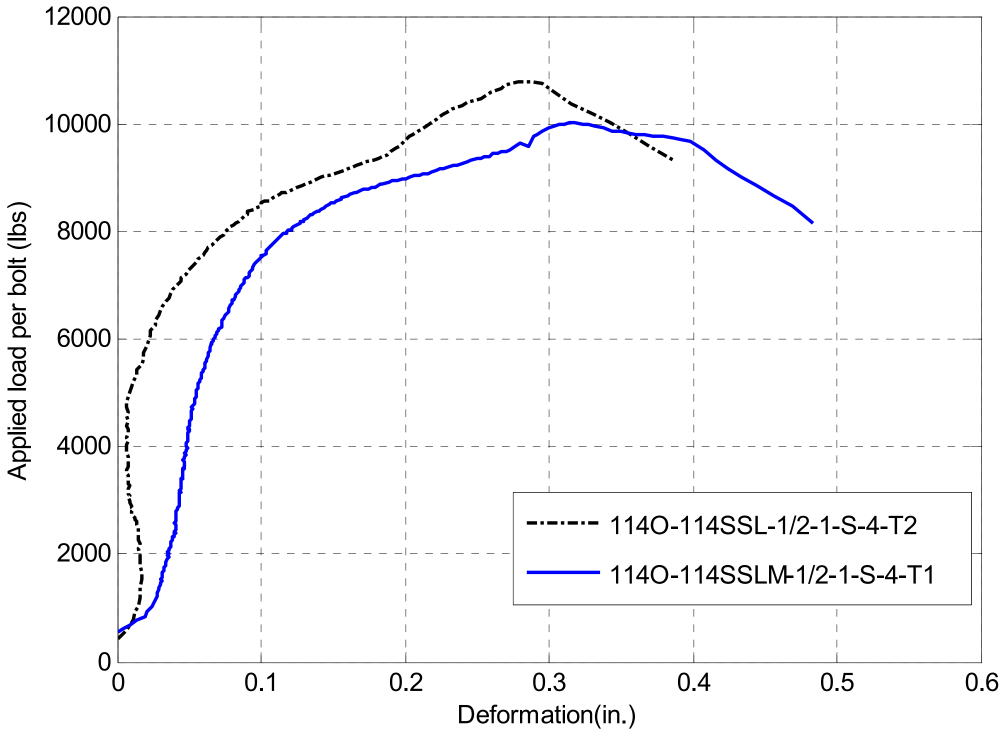

Fig 5.13 Load vs. Deformation Curves for Single Shear Connections with SSL and SSLM Slots

Fig 5.14 shows the failure mode of a 114 mil single shear connection with an oversized hole and a SSTM slot in two sheets respectively. Similar to the connection with a SSLM slot, the bolt tilted and went partially through the sheets. Fig 5.15 shows a comparison of load vs. deformation curves of connections with SST or SSTM slots.

Compared to the slots parallel to the axial load (SSL and SSLM), the slots perpendicular to the load (SST and SSTM) allowed greater bolt rotation and easier passage of the bolt through the sheets which yielded consistently lower connection strength.

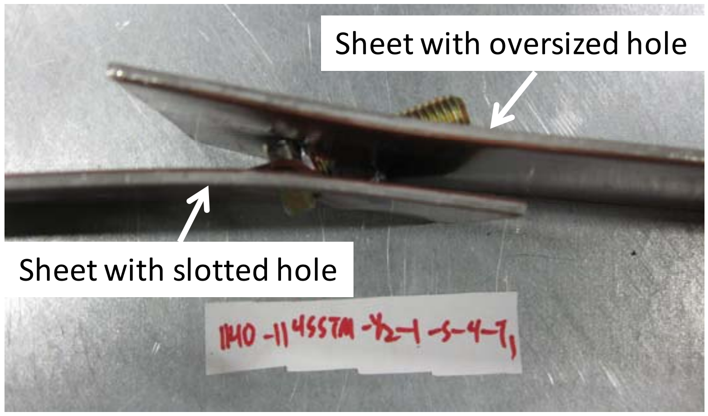

Fig 5.14 Bearing Failure of Test Specimen 114O-114SSTM-1/2-1-S-4-T1

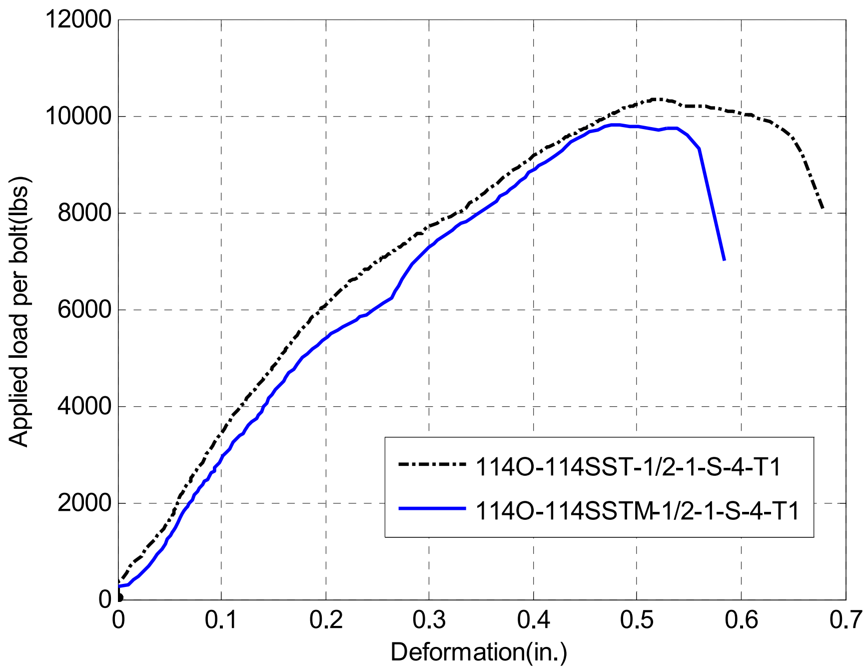

Fig 5.15 Load vs. Deformation Curves for Single Shear Connections with SST and SSTM Slots

For the double shear connections using the same type of sheets, bearing failure always occurred in the inside sheet. Fig 5.16 shows a 114 mil double shear connection that failed in the inside sheet which has an oversized hole while the outside sheets have SSTM slots. For some double shear connections using thinner outside sheets, the bearing failure occurred in the outside sheets. Fig 5.17 shows a bearing failure in the outside sheet of a double shear connection using 57 mil sheets on each side of a 94 mil sheet.

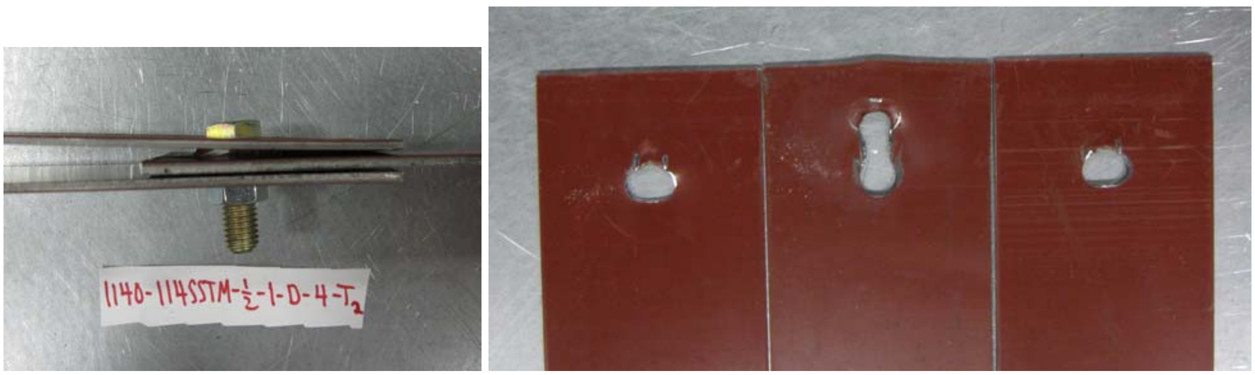

Fig 5.16 Bearing Failure of Test Specimen 114O-114SSTM-1/2-1-D-4-T2

Fig 5.17 Bearing Failure of Test Specimen 94O-57SST-1/2-1-D-4-T2

5.3 SHEAR FAILURE OF SHEET

5.3.1 Sheet Shear Failure for Connections with Oversized Holes

Shear failure was investigated by tension tests on connections with e/d =1.5. The test results for connections using oversized holes are provided in the Appendix Tables A-13 through A-15. Fig 5.18 shows a typical failure of a 57 mil single shear connection with e/d = 1.5. The bolt was tilted significantly in the single shear tests due to the eccentric loading and the oversized hole dimension. As a result, the sheet warped and the material piled up at the bearing area and extruded out the edge. Shearing of the sheets along parallel lines however, was not observed in the single shear connections. Fig 5.19 shows the load vs. deformation curves for two identical tests on 57 mil single shear connections with oversized holes and e/d=1.5.

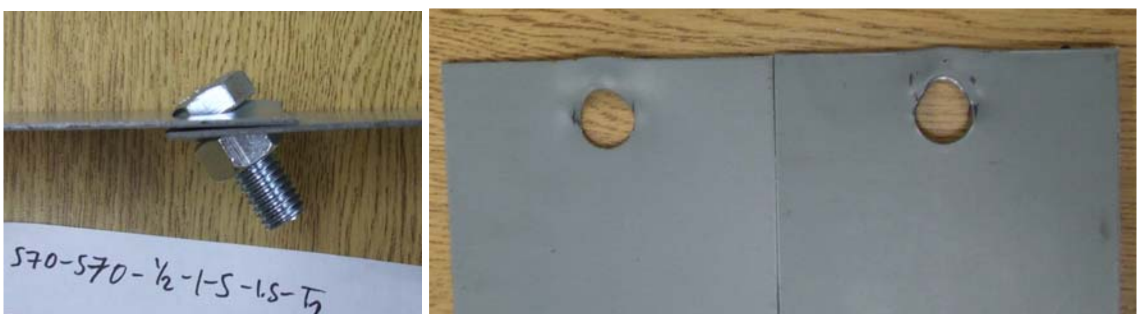

Fig 5.18 Shear Failure of Test Specimen 57O-57O-1/2-1-S-1.5-T2

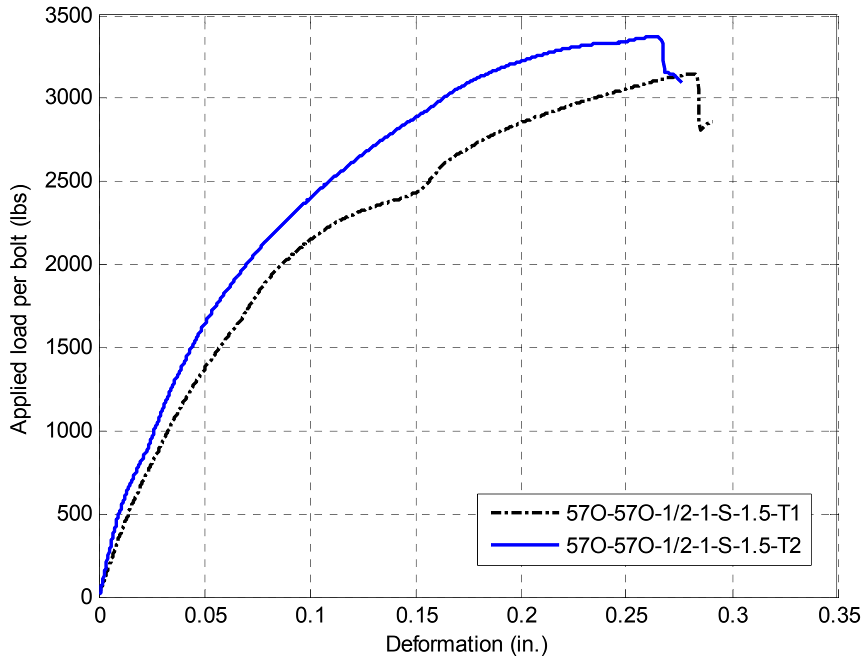

Fig 5.19 Load vs. Deformation Curves for 57 mil Single Shear Connections with e/d=1.5

For double shear connections, failure occurred in either the inside sheet or outside sheets. The results for double shear connections that failed in the inside sheet are listed in the Appendix Table A-15. Fig 5.20 shows a typical sheet shear failure in the inside sheet of a double shear connection. The material of the inside sheet at the bearing area was extruded off the edge and rupture was observed along parallel lines. Fig 5.21 shows the load vs. deformation curves for two 57 mil double shear connections that failed in the inside sheets.

Fig 5.20 Shear Failure of Test Specimen 57O-57O-1/2-1-D-1.5-T1

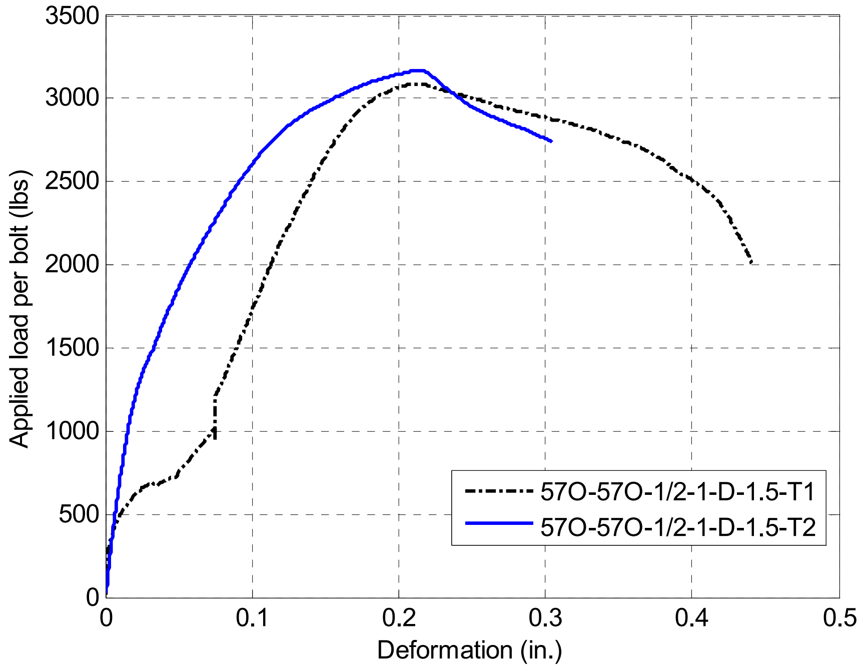

Fig 5.21 Load vs. Deformation Curves for 57 mil Double Shear Connections with e/d=1.5

Double shear connections using a 114 mil sheet fastened between two 57 mil sheets had significant deformation at all holes, and eventually failed by sheet shearing in the outside 57 mil sheets. Fig 5.22 shows the specimen after testing and Fig 5.23 illustrates the load vs. deformation curves for this particular specimen configuration.

Fig 5.22 Shear Failure of Test Specimen 114O-57O-1/2-1-D-1.5-T2

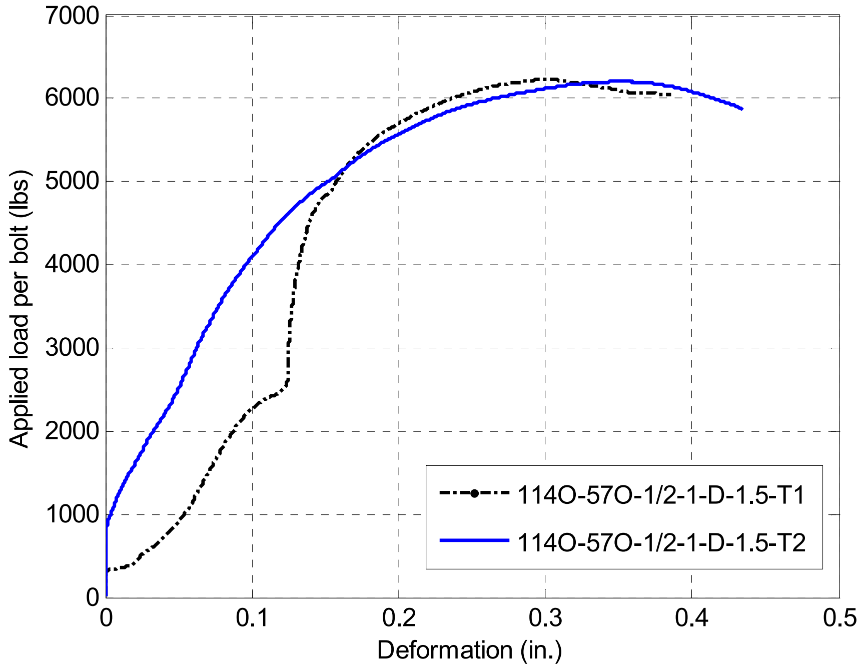

Fig 5.23 Load vs. Deformation Curves for 114 mil and 57 mil Double Shear Connections with e/d=1.5

5.3.2 Sheet Shear Failure for Connections with Oversized and Standard Holes

The test results for connections with oversized and standard holes, e/d=1.5, are provided in the Appendix Tables A-16 through A-18. Similar to the tests on connections with oversized holes, three failure types were observed in the connections with oversized and standard holes: single shear failure, double shear connection that failed in the inside sheet, and double shear connection that failed in the outside sheets. Fig 5.24 shows the failure mode of a 73 mil single shear connection. Fig 5.25 compares the load vs. deformation curves of 73 mil single shear connections with different hole configurations.

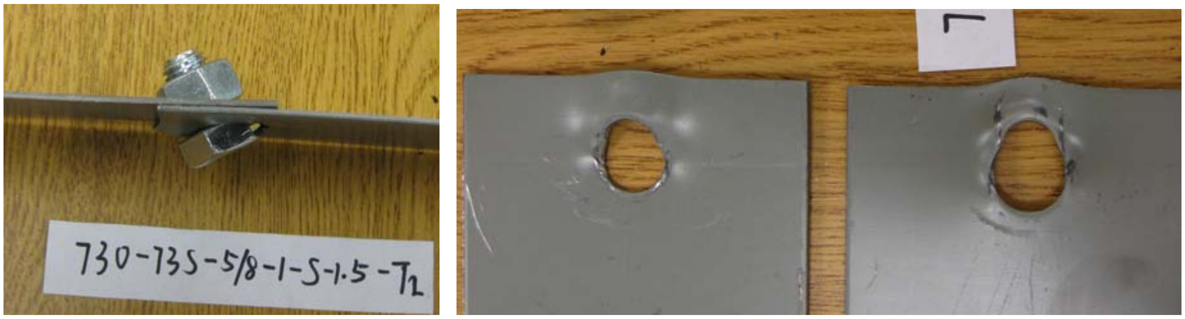

Fig 5.24 Shear Failure of Test Specimen 73O-73S-5/8-1-S-1.5-T2

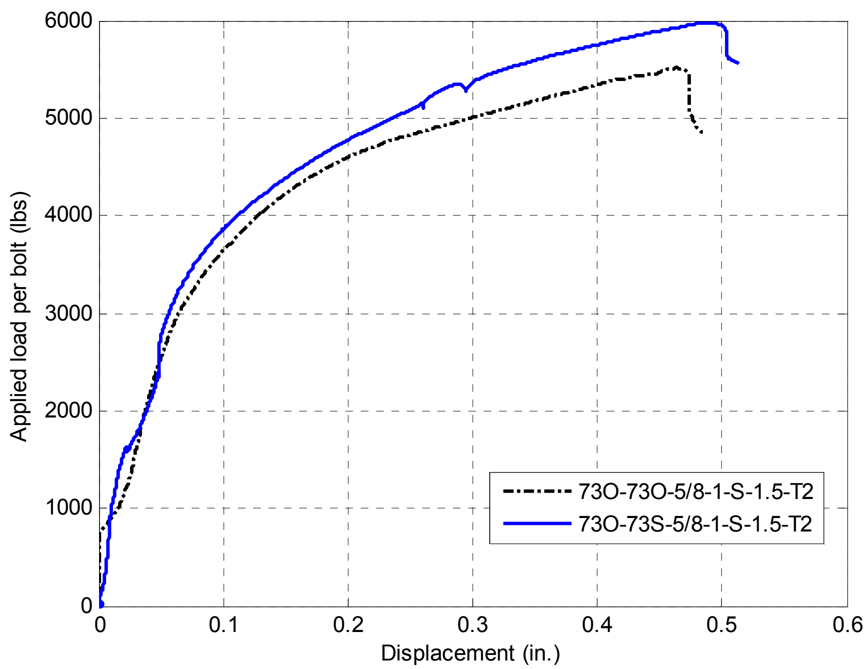

Fig 5.25 Load vs. Deformation Curves for 73 mil Single Shear Connections with e/d=1.5

Fig 5.26 shows a typical shear failure of a 73 mil double shear connection that failed in the inside sheet. The bolt remained straight after test while the inside sheet material was extruded off the end.

Fig 5.26 Shear Failure of Test Specimen 73O-73S-1/2-1-D-1.5-T1

The double shear connections with a 43 mil inside sheet and 27 mil outside sheets failed by shearing in the outside sheets as shown in Fig 5.27. Fig 5.28 illustrates the load vs. deformation curves for this connection configuration.

Fig 5.27 Shear Failure of Test Specimen 43O-27S-3/8-1-D-1.5-T2

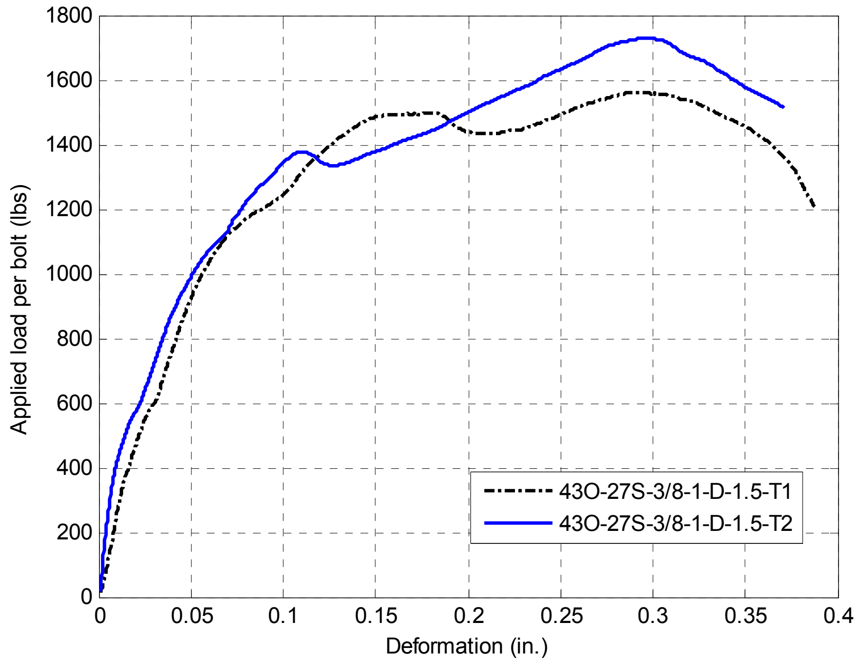

Fig 5.28 Load vs. Deformation Curves for Double Shear Connections Failed in Outside Sheets, e/d=1.5

5.3.3 Sheet Shear Failure for Connections with Oversized and Slotted Holes

The test results for connections with oversized and slotted holes, e/d=1.5, are provided in the Appendix Tables A-19 through A-21. Fig 5.29 shows the failure mode for a 73 mil single shear connection using an oversized hole and a SST slot in two sheets. The bolt rotated and partially went through the holes causing separation of the two sheets. Fig 5.30 compares the load vs. deformation curves for 73 mil single shear connections with an oversized hole and a SST or SSTM slotted hole. The larger dimension of SSTM slots allowed more bolt rotation and resulted in lower connection strength than SST slots.

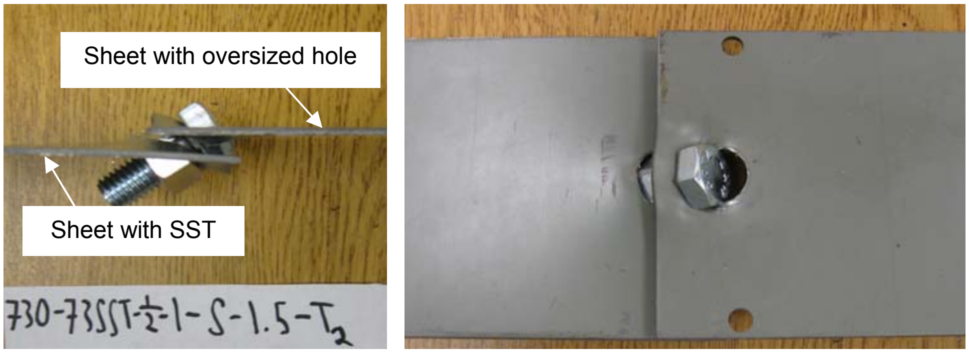

Fig 5.29 Shear Failure of Test Specimen 73O-73SST-1/2-1-S-1.5-T2

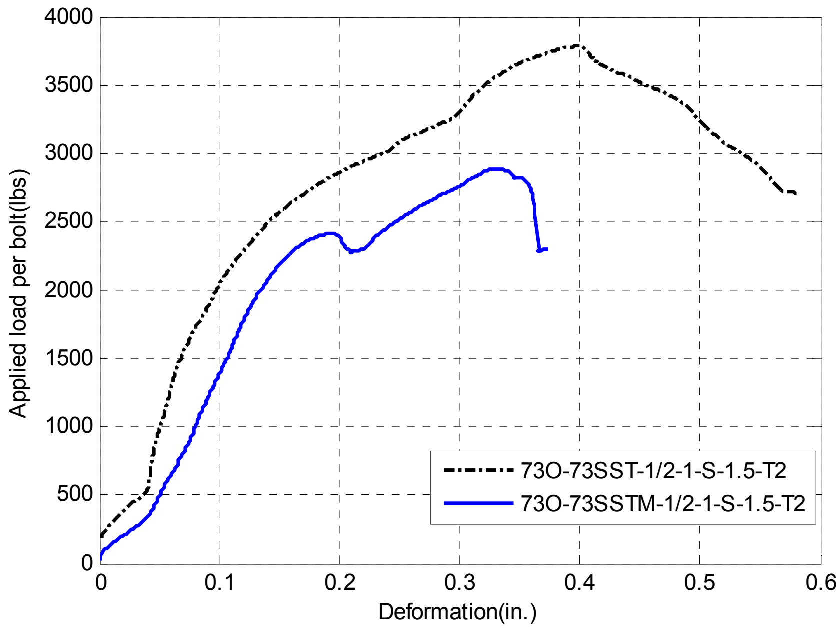

Fig 5.30 Load vs. Deformation Curves for 73 mil Single Shear Connections with Oversized Hole and SST or SSTM Slot, e/d=1.5

Fig 5.31 shows the failure mode for a 94 mil single shear connection with an oversized hole and a SSLM slot. Fig 5.32 compares the load vs. deformation curves for the 94 mil single shear connections with an oversized hole and SSL or SSLM slotted hole. The two connections had similar behavior and peak load. Fig 5.33 shows a shear failure in the outside sheets of a double shear connection. Fig 5.34 compares the load vs. deformation curves for a test specimen comprised of a 114 mil inner sheet and two 57 mil outer sheets that failed in the outer sheets.

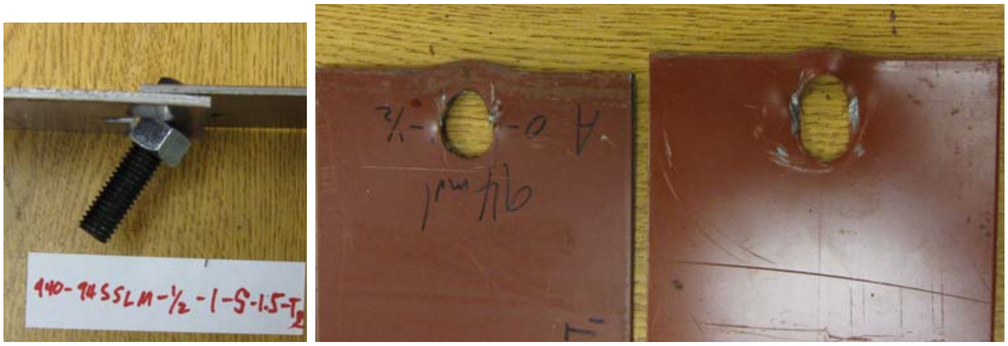

Fig 5.31 Shear Failure of Test Specimen 94O-94SSLM-1/2-1-S-1.5-T2

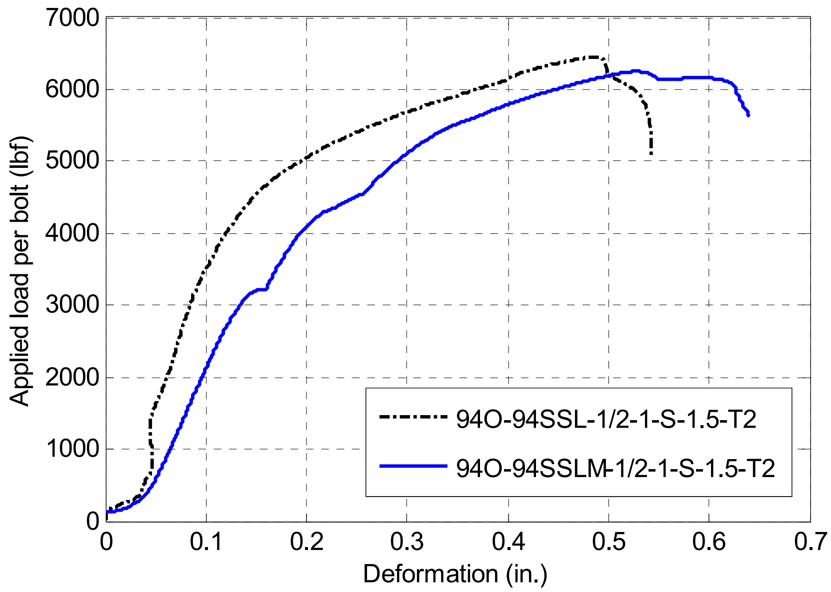

Fig 5.32 Load vs. Deformation Curves for 94 mil Single Shear Connections with Oversized Hole and SSL or SSLM Slot, e/d=1.5

Fig 5.33 Shear Failure of Test Specimen 114O-57SSL-1/2-1-D-1.5-T2

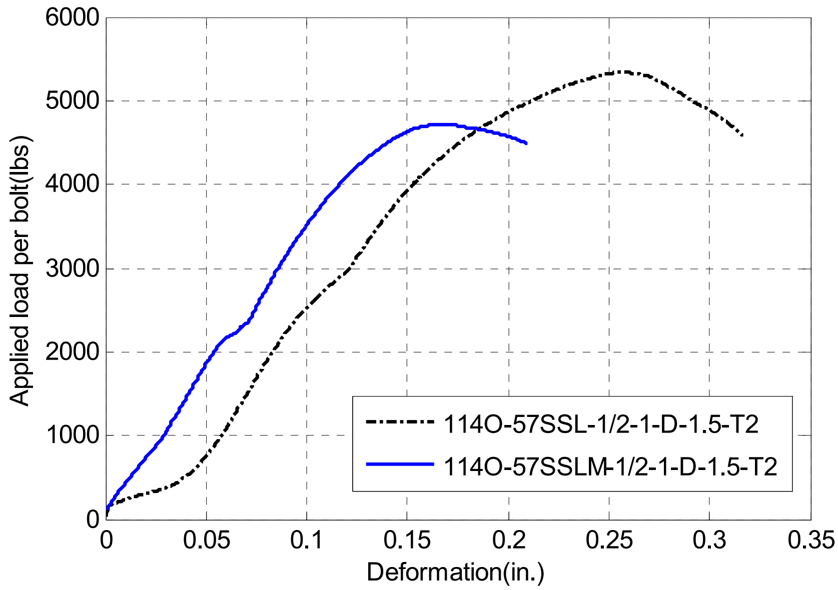

Fig 5.34 Load vs. Deformation Curves for Double Shear Connections Failed in Outside Sheets, e/d=1.5

For double shear connections comprised of sheets with the same thickness, the shear failure occurred in the inside sheet, which always had an oversized hole in this test program. Fig 5.35 shows the failure mode of a 94 mil double shear connection. Since the failure was in the inside sheet, the different hole configurations in the outside sheets did not influence the strength of the double shear connection.

Fig 5.35 Shear Failure of Test Specimen 94O-94SSTM-1/2-1-D-1.5-T2

5.4 RUPTURE IN NET SECTION OF SHEET

The rupture of the sheet in the net section was investigated by tests on single shear connections with an oversized hole in one sheet and various hole configurations in the other sheet. Two d/s ratios were studied: 0.2 and 0.4. The test results are summarized in Appendix Table A-22. The P_{NAS-US} in Table A-22 is the predicted nominal tensile strength by the AISI S100 provisions applicable to the United States (Eq. E3.2-3 in Appendix A of AISI S100). The $P_{NAS-CAN}$ in Table A-22 is the predicted nominal tensile strength by AISI S100 provisions applicable to Canada (Eq. C2.2-1 in Appendix B of AISI S100).

Fig 5.36 shows an observed rupture failure in a 73 mil single shear connection with oversized holes and d/s=0.4. The bolt tilted and the two sheets separated. Rupture in the net section of the sheet across the center of the hole was observed. Fig 5.37 shows the load vs. deformation curves for the 73 mil single shear connections that failed in net section rupture. Both tests showed slippage when the loads were at approximately 500 lbs. Afterwards the bolt and the bearing side of the sheets became firmly in contact, the loads began to increase linearly followed by some inelastic deformation before the peak loads were reached,and then an abrupt loss of resistance (load).

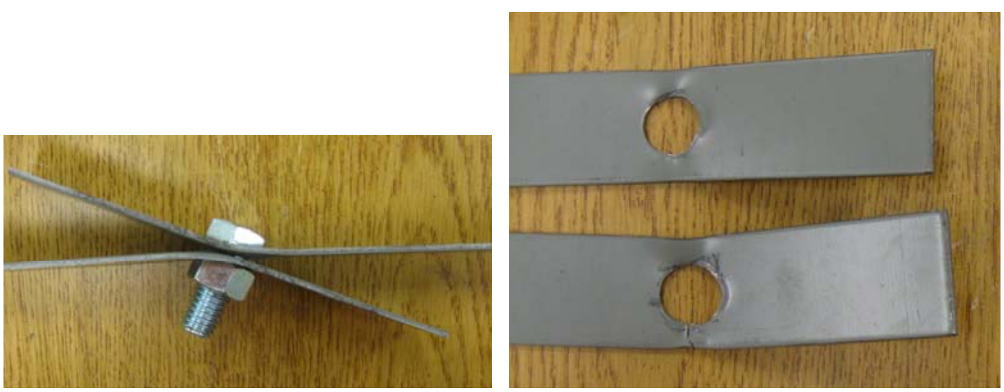

Fig 5.36 Rupture Failure of Test Specimen 73O-73O-1/2-1-S-0.4-T1

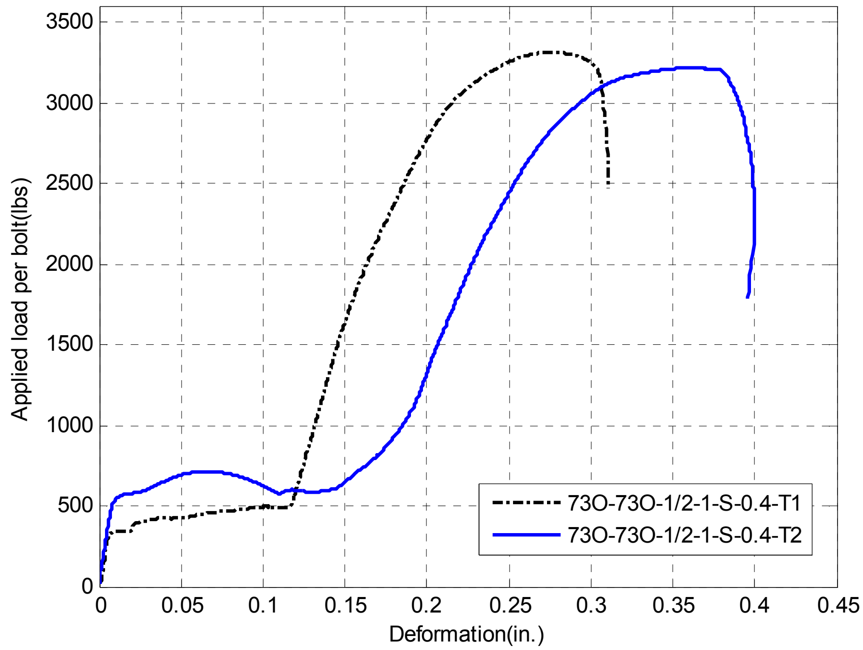

Fig 5.37 Load vs. Deformation Curves for 73 mil Single Shear Connections with Oversized Holes, d/s=0.4

A similar failure mechanism was also observed in the single shear connections with oversized and slotted holes. Fig 5.38 shows a 73 mil connection with an oversized and a SSL slotted hole. Fig 5.39 shows the load vs. deformation curves of two identical 73 mil single shear connections. Both connections demonstrated significant slippage before the load bearing started to develop.

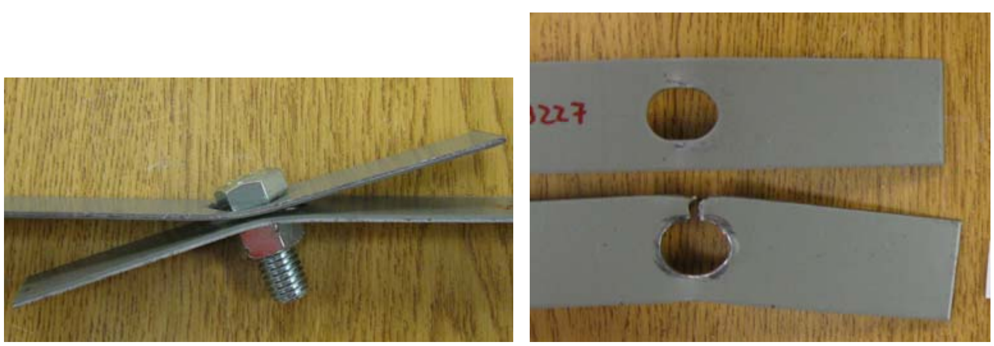

Fig 5.38 Rupture Failure of Test Specimen 73O-73SSL-1/2-1-S-0.4-T1

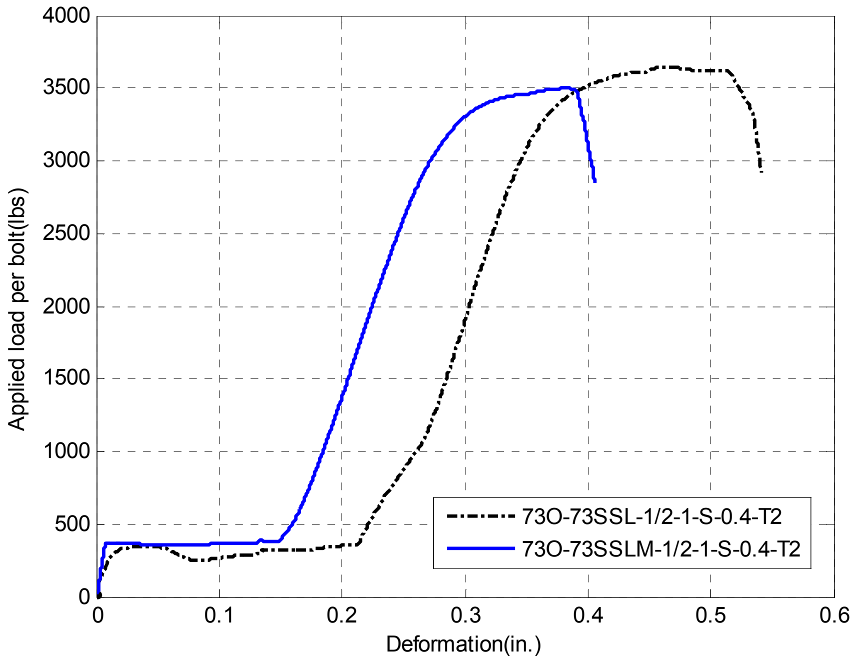

Fig 5.39 Load vs. Deformation Curves for 73 mil Single Shear Connections with Oversized Holes and SSL or SSLM Slotted Holes, d/s=0.4

For connections with d/s=0.2, the single shear connections exhibited a bearing failure mode and net section rupture was not observed. Fig 5.40 shows the failure of a 73 mil single shear connection with d/s=0.2, the bolt rotated and both the head and nut partially went through the holes.

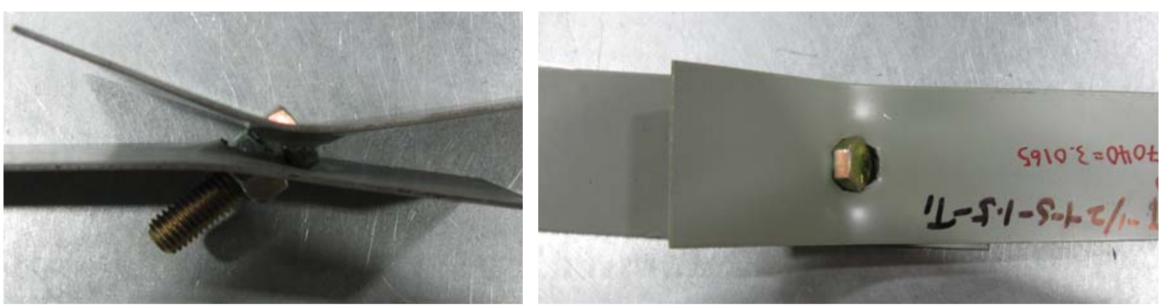

Fig 5.40 Failure Mode of Test Specimen 73O-73SST-1/2-1-S-0.2-T1

6. DISCUSSION

6.1 SHEET BEARING STRENGTH

6.1.1 Sheet Bearing Strength of Bolted Connections Using Oversized Holes without Washers

6.1.1.1 Bearing in Single Shear and Outside Sheets of Double Shear Connections

Previous research (LaBoube and Yu 1995, Wallace, Schuster, and LaBoube 2001a) discovered that the bearing failure of single shear connections and the bearing failure in the outside sheets of double shear connections have similar behavior and strength. The AISI S100 (2007) adopts same design equations (Eq. 2-3) and design factors (LRFD resistance factor and ASD safety factor) for those two bearing failure types. The AISI S100 formula for bearing factor C is listed in Table 2-2. AISI S100 uses m_f = 0.75 for bearing in single shear and outside sheets of double shear connections.

A total of 90 single shear connection and double shear connection tests with failure in the outside sheets were conducted in both Phases 1 and 2. Fig 6.1 compares the test results with the current AISI S100 predictions. The y axis is a normalized strength which is equivalent to the product of C and m_f factors. The figure shows that the test data from both phases are well mixed and form the same trend of bearing strength with regard to the d/t ratio. The figure also indicates that for a d/t ratio greater than 7 the tested bearing strength is systematically lower than the AISI S100 predictions. For a d/t ratio less than 7, the average test results are consistently lower than the AISI S100 predictions. On average, the AISI S100 (2007) design yields 18% non-conservative predictions for bearing strength of the tested single shear and outside sheets of double shear bolted connections when oversized holes without washers are used. Table 6-1 summarizes the test-to-predicted ratios.

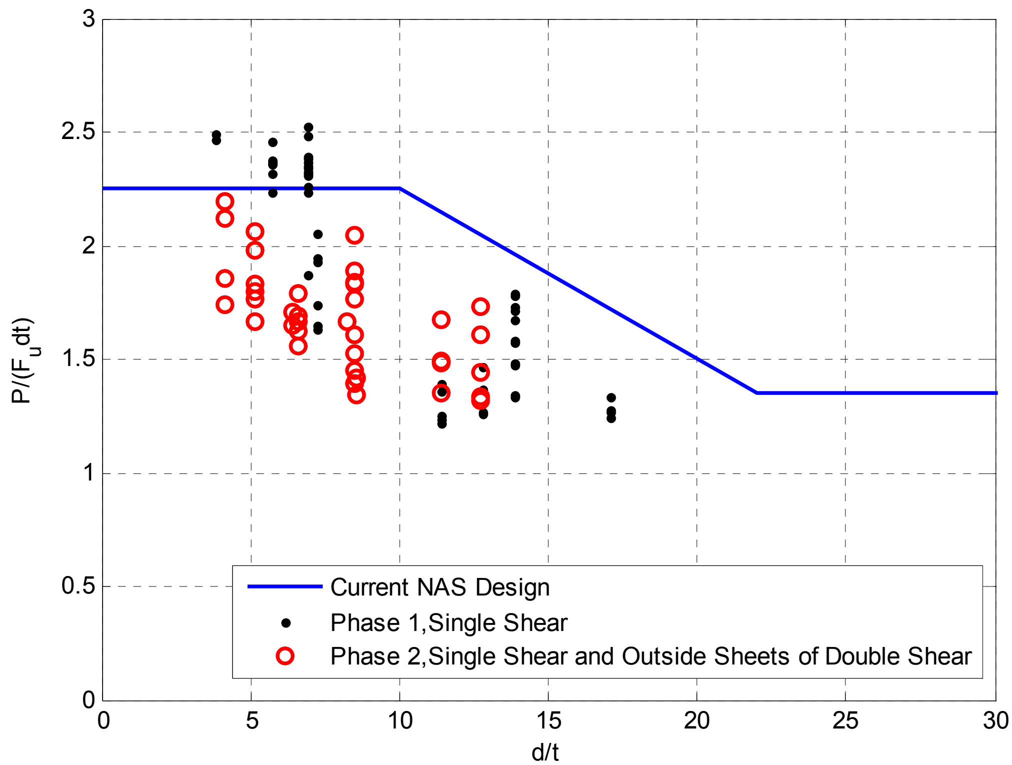

Fig 6.1 Test Results vs. AISI S100 Predictions for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized Holes without Washers

Table 6-1 Test-to-Predicted Ratios for Sheet Bearing Strength of Single Shear and Outside Sheets of Double Shear Connections with Oversized Holes

		Single shear	Outside sheets of double shear	Overall
No. of tests		78	12	90
P_{test}/P_{NAS}	Average	0.83	0.77	0.82
	Std. deviation	0.16	0.08	0.15
	COV	0.192	0.110	0.185
P_{test}/P_{new1}	Average	1.00	1.03	1.01
	Std. deviation	0.15	0.09	0.15
	COV	0.154	0.090	0.147
P_{test}/P_{new2}	Average	0.96	0.94	0.96
	Std. deviation	0.16	0.09	0.15
	COV	0.164	0.093	0.157

In order to accurately predict the bearing strength of the CFS bolted connections using oversized holes without washers, two revised AISI S100 design methods are proposed according to the overall test results. The revised methods adopt the existing bearing equation in AISI S100 (2007), Eq. 2-3, with revised formulae and values for the bearing factor, C, and the modification factor, m_f.

Tables 6-2 and 6-3 list the proposed bearing factor and modification factor respectively. Fig 6.2 shows the comparison of the test results with the original AISI S100 and proposed design methods. The y axis is the normalized peak loads, $P_{test}/(F_u\ d\ t)$, which is equivalent to the product of the bearing factor and the modification factor ($C\ m_f$). For both proposed new methods, the upper and lower bounds of factor C are kept the same as found in the current AISI S100, but the transition points are proposed to be lower than the AISI S100 values in order to better match the test data. Fig 6.2 indicates that a non-linear trend of C factor exists at an intermediate range of d/t ratio between the two transition points. The new method #1 adopts a non-linear curve for the C factor for the intermediate range of d/t. Wallace, Schuster, and LaBoube (2001a) also developed a non-linear function for C factor between the two transition points. The new method #2 however uses a linear transition for the C factor in the intermediate d/t range, which is consistent with the approach of the current AISI S100 design equation.

For the modification factor, lower values are proposed to reflect the reduction in the bearing strength discovered in this research project. For bearing in singe shear or outside sheets of double shear connections, m_f = 0.68 is proposed. Bearing failures in the inside sheet of double shear connections will be discussed in detail in the following Section 6.1.1.2. The proposed two new methods adopt the same modification factor m_f as listed in Table 6-3.

Table 6-2 Proposed Bearing Factor, C, for Bolted Connections with Oversized Holes

Ratio of fastener diameter to member thickness, d/t	New method #1	New method #2
d/t < 7	3	3
7 ≤ d/t ≤ 18	1+14/(d/t)	3.762-0.109(d/t)
d/t > 18	1.8	1.8

Table 6-3 Proposed Modification Factor, m_f, for Bolted Connections with Oversized Holes

Type of bearing connection	m_f
Single shear and outside sheets of double shear connections with oversized holes without washers under both bolt head and nut	0.68
Inside sheet of double shear connections with oversized holes without washers	1.11

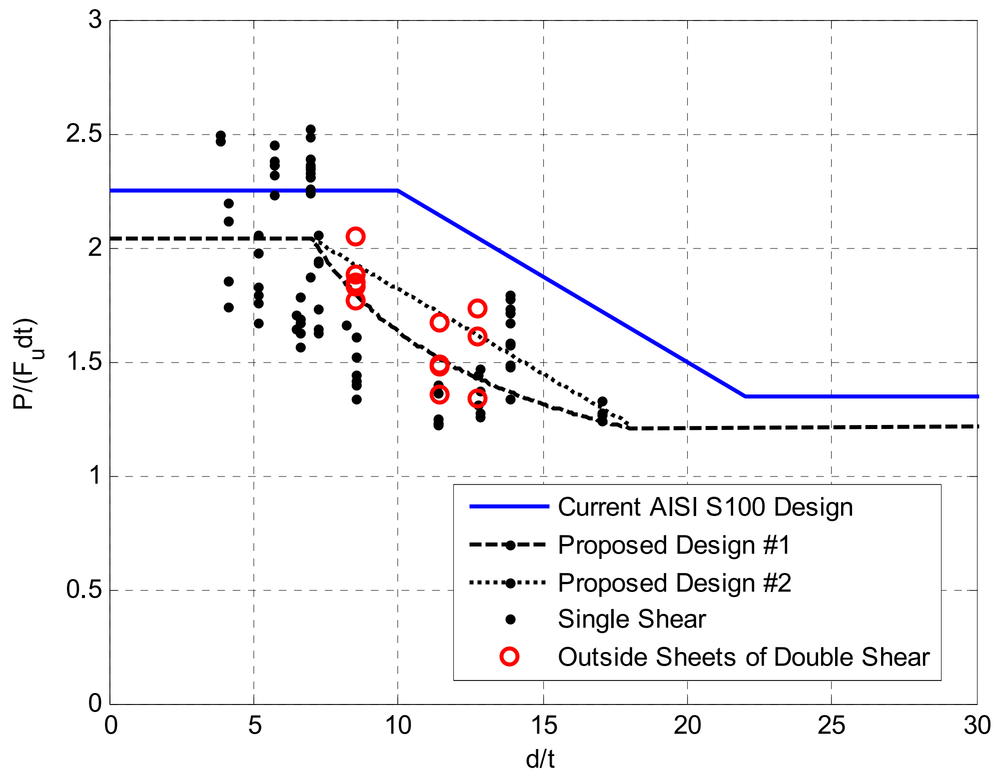

Fig 6.2 Test Results vs. Predictions for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized Holes without Washers

The test-to-predicted ratios for the new design methods are listed as P_{test}/P_{new1} and P_{test}/P_{new2} in the Appendix Tables A-1 through A-3. On average, the new method #1 gives an average test-to-predicted ratio of 1.01 with a coefficient of variation 0.147. The new method #2 yields an average test-to-predicted ratio of 0.96 with a coefficient of variation 0.157.

For the proposed bearing strength method, the resistance factors, ϕ for LRFD and LSD design methods were determined in accordance with Chapter F of AISI S100 (2007) with a target reliability index, β, of 3.5 and 4.0 for LRFD and LSD respectively. The resistance factors, ϕ, can be determined by the following Equation.

$$\phi = C_\phi (M_m F_m P_m) e^{-\beta\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \quad (6\text{-}1)$$

where: C_ϕ =calibration coefficient (1.52 for LRFD, 1.42 for LSD);

M_m = mean value of material factor;

F_m = mean value of fabrication factor;

P_m = mean value of professional factor;

β = target reliability index;

V_M =coefficient of variation of material factor;

V_F = coefficient of variation of fabrication factor;

C_p = coefficient factor;

V_P = is coefficient of variation of test results;

V_Q = coefficient of variation of load factor (0.21 for LRFD and LSD).

The values of M_m V_M F_m and V_F were taken from Table F1 in AISI S100 (2007). The safety factor for ASD design can be determined by the Equation 6-2.

$$\Omega = \frac{1.2\,{}^{D}\!/\!_{L} + 1.6}{\Phi({}^{D}\!/\!_{L} + 1)} = 1.533/\Phi \quad (6\text{-}2)$$

where D/L, the dead to live load ratio, is 1/5 which is consistent with the ratio used by Wallace, LaBoube, and Schuster (2001b).

Table 6-4 summarizes the calculated resistance factors and safety factors as well as the adopted factors in AISI S100 (2007). The new method #1 yields higher resistance factors and lower safety factor than those used in AISI S100 (2007). The new method #2 has similar resistance factors as those in AISI S100. The computed safety factor is slightly greater than the AISI S100 value. The new method #1 has better performance than the method #2 due to better agreement with the test data. Both methods give better or similar performance than the current AISI S100 design for bearing strength.

The new method #1 is therefore recommended for bolted connections using oversized holes without washers. However the new method #2 can also be accepted as an alternative method.

Table 6-4 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized Holes without Washers

	Single shear and outside sheets of double shear connections using oversized holes without washers		
	New method #1	New method #2	
Quantity	90	90	
Mean	1.01	0.96	
Std. Dev.	0.15	0.15	
COV	0.147	0.157	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	1.01	0.96	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.65	0.60	0.60
ϕ (LSD)	0.53	0.49	0.50
Ω (ASD)	2.37	2.55	2.50

The low ductility steel was investigated in Phase 1 in which 11 single shear connections were tested. Fig 6.3 illustrates a comparison of the single shear connections using low ductility steel with those using high ductility steel. The two groups of data are well mixed. For the low ductility steel connections, the test-to-predicted ratio is 0.99 for the proposed new method #1 and 0.91 for the method #2. It indicates that the full tensile strength can be used to predict the bearing strength of the tested low ductility steel connections. The two proposed methods work fine for the tested connections. However, due to the limited amount of test data, the validation of the proposed methods for low ductility steel connections with the use of full tensile strength in design should be further studied in future projects.

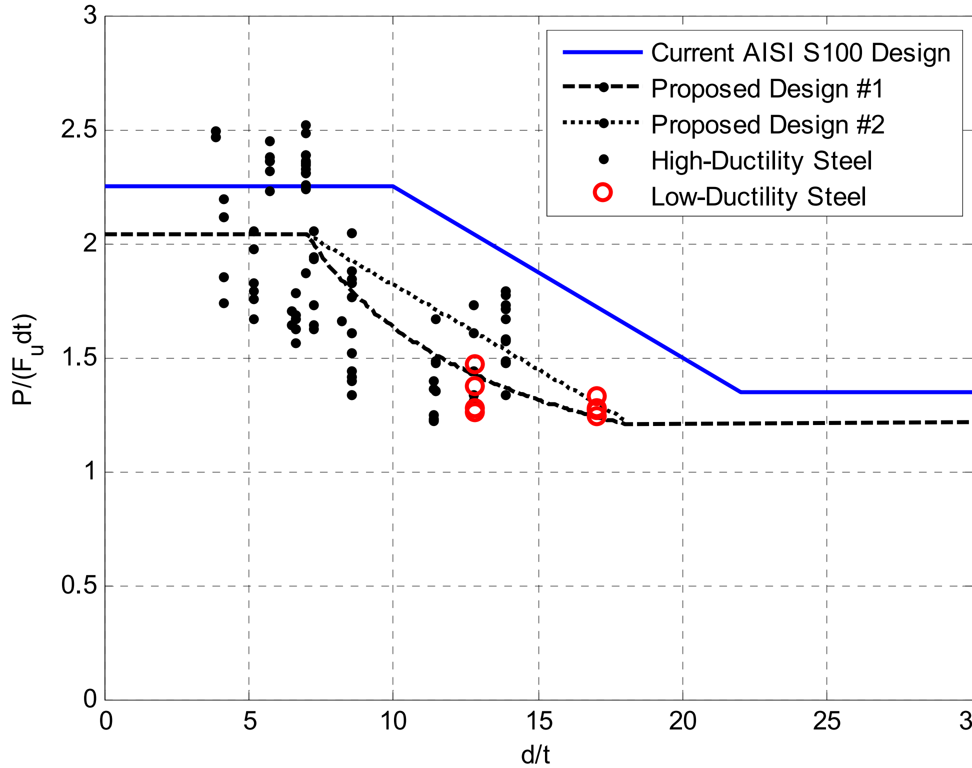

Fig 6.3 Single Shear Connections using Low-Ductility and High-Ductility Steel

6.1.1.2 Bearing in Inside Sheets of Double Shear Connections

In both Phases 1 and 2, a total of 47 double shear connections failed by bearing in the inside sheet. Fig 6.4 shows the comparison of test results with the AISI S100 predictions. The test results show good agreement and form a clear trend of the bearing strength with respect to the d/t ratio. The AISI S100 (2007) design provisions yield systematically higher nominal strength than the tested peak loads. The average test-to-predicted ratio is 0.76 for the AISI S100 method. The statistical results are listed in Table 6-5.

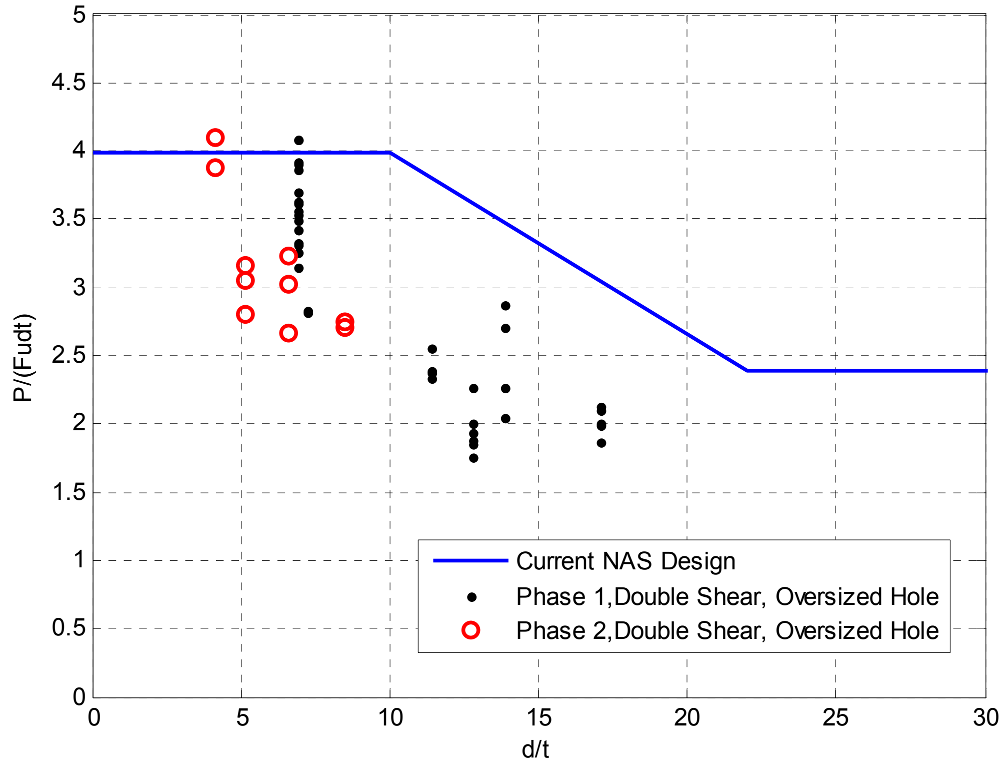

Fig 6.4 Test Results vs. AISI S100 Predictions for Bearing Failure in Inside Sheet of Double Shear Connections with Oversized Holes

Table 6-5 Test-to-Predicted Ratios for Sheet Bearing Strength of Inside Sheet of Double Shear Connections with Oversized Holes

No. of tests		47
P_{test}/P_{NAS}	Average	0.76
	Std. deviation	0.15
	COV	0.198
P_{test}/P_{new1}	Average	1.00
	Std. deviation	0.13
	COV	0.129
P_{test}/P_{new2}	Average	0.96
	Std. deviation	0.15
	COV	0.152

To account for the reduced bearing strength for the inside sheet of double shear connections, the two proposed new methods described in the previous section can be adopted again but with a specific modification factor for this bearing type, m_f = 1.11. The proposed new modification factor is listed in Table 6-3.

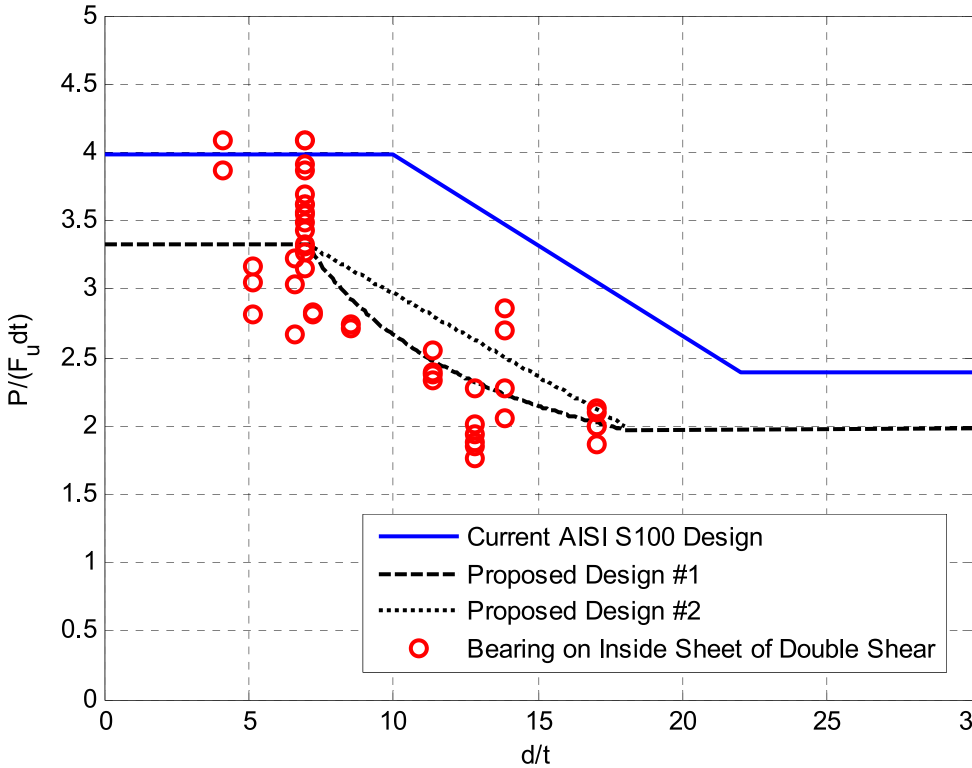

Fig 6.5 Test Results vs. Predictions for Bearing Failure in Inside Sheet of Double Shear Connections with Oversized Holes

The test-to-predicted ratios for the two new methods are listed in the Appendix Table A-4. Fig 6.5 shows the comparison of the test results with the proposed design methods. On average, the new method #1 gives better agreement with the test results than the new method #2. Table 6-5 summarizes the test-to-predicted ratios for both the new methods and the AISI S100 method.

For the proposed bearing strength methods, the resistance factors, ϕ for LRFD and LSD design methods and the safety factor, Ω, for the ASD design method were determined using the same approach described in the previous section. Table 6-6 summarizes the computed results as well as the existing factors in AISI S100 (2007). Both new methods reach the same reliability level as the current AISI S100 design method. The new method #1 gives the highest resistance factors and lowest safety factor among the three methods and is therefore recommended for determining the nominal bearing strength of the inside sheet of CFS bolted double shear connections using oversized holes without washers. The new method #2 is also acceptable as an alternative method.

Table 6-6 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Inside Sheet of Double Shear Connections Using Oversized Holes without Washers

	Inside sheet of double shear connection using oversized holes without washers		
	New method #1	New method #2	
Quantity	47	47	
Mean	1.00	1.00	
Std. Dev.	0.13	0.13	
COV	0.129	0.152	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	1.00	0.96	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.66	0.61	0.60
ϕ (LSD)	0.54	0.49	0.50
Ω (ASD)	2.33	2.53	2.50

Bearing failure in the inside sheet of double shear connections using low ductility steel was studied in Phase 1. A total of 8 tests were conducted. Fig 6.6 illustrates a comparison of the double shear connections using low ductility steel with double shear connections using high ductility steel. The test data of the low ductility steel connections are located at the lower bound of the data set of high ductility steel connections. The difference between the two groups is not significant enough to form two different trends of the relation between the normalized strength and the d/t ratio. For the low ductility connections, the test-to-predicted ratio is 0.91 for the proposed new method #1 and 0.84 for method #2. It should noted that the full tensile strength is used for calculating the test-to-predicted ratios. Because of the limited number of tests, the validation of the proposed methods for inside sheet of double shear connections using low ductility steel should be further studied.

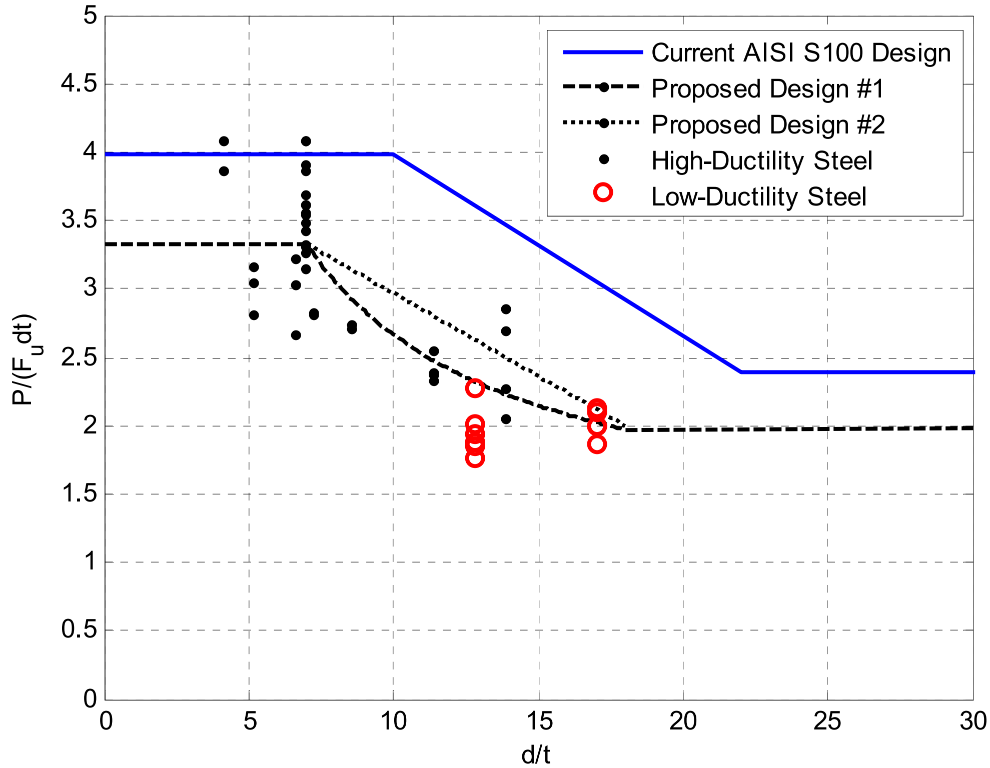

Fig 6.6 Double Shear Connections using Low-Ductility and High-Ductility Steel with Bearing Failure in Inside Sheet

6.1.2 Sheet Bearing Strength of Bolted Connections Using Oversized and Standard Holes without Washers

6.1.2.1 Bearing in Single Shear and Outside Sheets of Double Shear Connections

The test results for bearing in single shear and outside sheets of double shear connections are listed in the Appendix Tables A-5, A-6 and A-7. It is found that the connections using the combined hole configurations give higher strength than those with oversized holes in all sheets. The increase in connection strength is caused by smaller gaps between the bolt and the standard hole, which results in less rotation of the bolt in the tests. Table 6-7 lists the direct comparison of average peak loads between the connections with combined holes and those using only oversized holes. On average, the combined hole configurations yield an average 3.78% increase in bearing strength than the connections with only oversized holes.

Table 6-7 Average Peak Loads of Single Shear Connections with Oversized and Standard Holes in Bearing

Sheet thickness	Average peak load (lbs)		P_{SO}/P_{OO}-1
	P_{OO} Oversized holes	P_{SO} Standard and oversized holes	
114 mil	10418	11274	8.22%
94 mil	8638	9262	7.22%
73 mil	5239	5690	8.61%
57 mil	3242	3602	11.10%
43 mil	1802	1839	2.05%
30 mil	924	949	2.71%
43 mil + 30 mil	2069	2282	10.29%
57 mil + 43 mil	4937	4970	0.67%
94 mil + 57 mil	8293	7563	-8.80%
114 mil + 57 mil	8007	7662	-4.31%
Average			3.78%

Fig 6.7 illustrates a comparison between two hole configurations. The two groups of test data are well mixed and the data points of connections with combined holes are within the bounds of the test data of connections with oversized holes. The proposed two new methods for bearing strength should be applicable to those connections with standard and oversized holes. The resistance factors and safety factors are calculated using the same method as described in Section 6.1.1.1 and listed in Table 6-9.

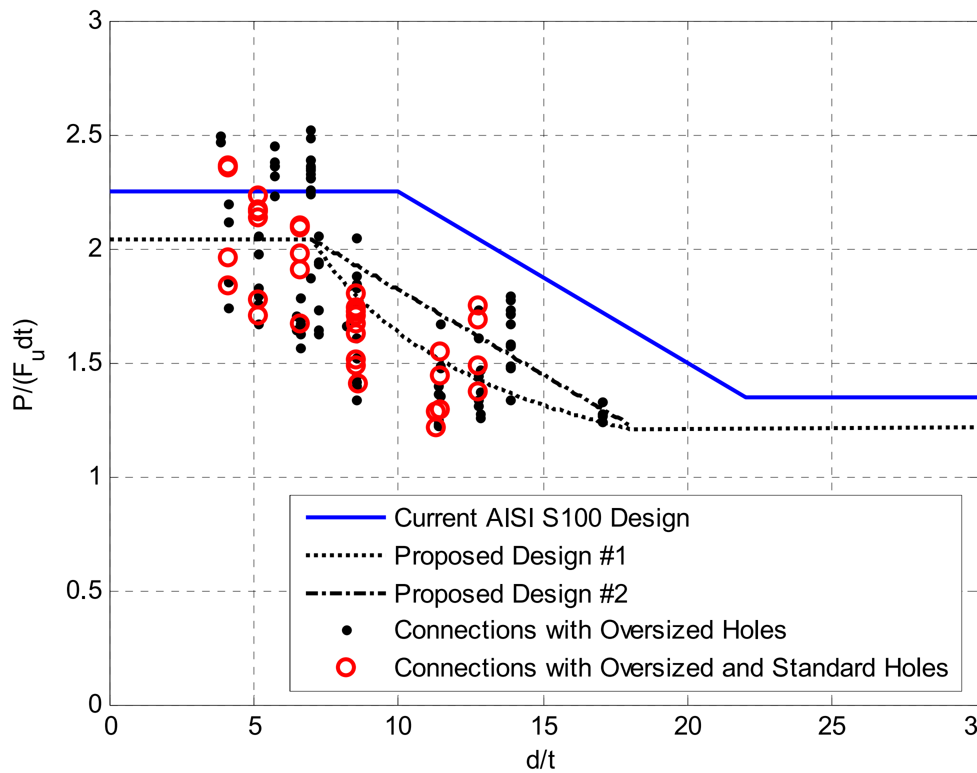

Fig 6.7 Test Results vs. Design Methods for Bearing Strength of Single Shear and Outside Sheets of Double Shear Connections

Table 6-8 Test-to-Predicted Ratios for Bearing Strength of Single Shear and Outside Sheets of Double Shear Connections with Oversized and Standard Holes

No. of tests = 35	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
Average	0.77	0.94	0.89
Std. deviation	0.12	0.12	0.12
COV	0.152	0.124	0.130

Table 6-9 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized and Standard Holes without Washers

	Single shear and outside sheets of double shear connection using oversized and standard holes without washers		
	New method #1	New method #2	
Quantity	35	35	
Mean	0.94	0.89	
Std. Dev.	0.12	0.12	
COV	0.124	0.130	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	0.94	0.89	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.62	0.58	0.60
ϕ (LSD)	0.51	0.48	0.50
Ω (ASD)	2.46	2.63	2.50

6.1.2.2 Bearing in Inside Sheets of Double Shear Connections

Fig 6.8 illustrates the comparison between double shear connections using two hole configurations, oversized holes vs. oversized and standard hole combined, with failure occurring in the inside sheet. A total of 8 tests were conducted for the combined hole configuration. The two groups of test data are well mixed as can be seen in the figure. The two new methods work well for the combined hole configuration with the average test-to-predicted ratio 1.03 and 1.02 respectively. The AISI S100 design gives 16% non-conservative predictions for those double shear connections with combined holes. Table 6-10 summarizes the test-to-predicted ratios. It can be concluded that the proposed bearing design methods for the oversize hole configuration are applicable to the standard and oversize hole combined configuration. The use of standard hole in the connections increase the bearing strength but the increase is not significant because the oversized hole still controls the connection's bearing strength. Table 6-11 summarizes the computed resistance factors and safety factors for the design methods.

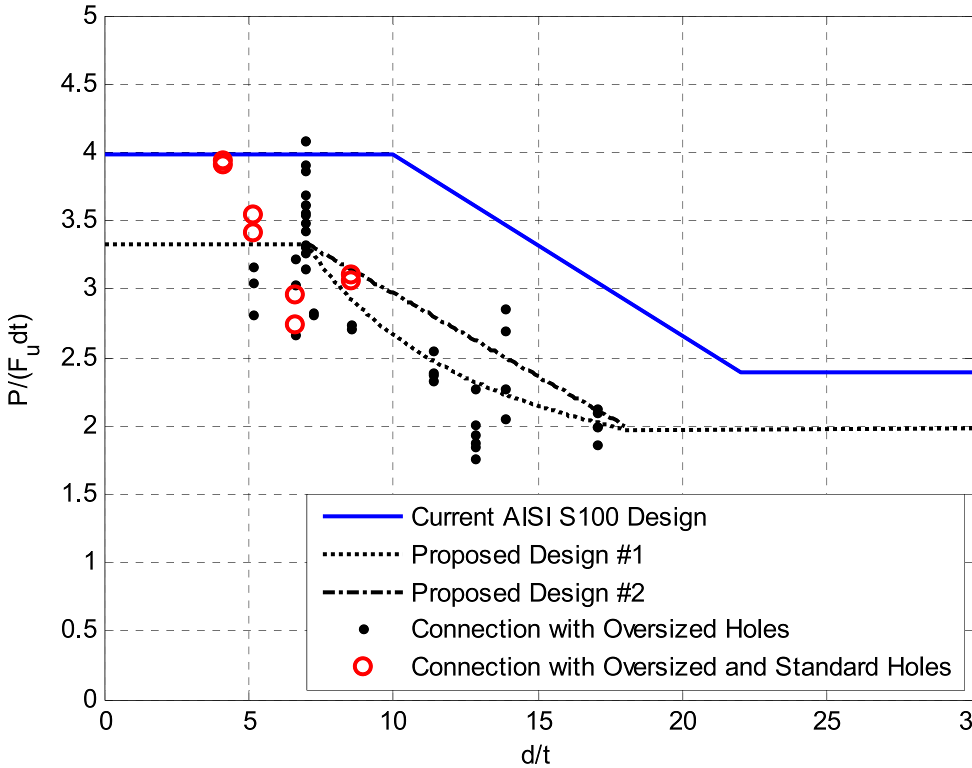

Fig 6.8 Test Results vs. Design Methods for Bearing Strength of Double Shear Connections with Oversized Holes and Standard Holes

Table 6-10 Test-to-Predicted Ratios for Bearing Strength of Inside Sheet of Double Shear Connections with Oversized and Standard Holes

No. of tests = 8	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
Average	0.84	1.03	1.02
Std. deviation	0.11	0.12	0.12
COV	0.132	0.119	0.123

Table 6-11 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Inside Sheet of Double Shear Connections Using Oversized and Standard Holes without Washers

	Inside sheet of double shear connections using oversized and standard holes without washers		
	New method #1	New method #2	
Quantity	8	8	
Mean	1.03	1.02	
Std. Dev.	0.12	0.12	
COV	0.119	0.123	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	1.03	1.02	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.66	0.65	0.60
ϕ (LSD)	0.54	0.53	0.50
Ω (ASD)	2.33	2.37	2.50

6.1.3 Sheet Bearing Strength of Bolted Connections Using Oversized and Slotted Holes without Washers

6.1.3.1 Bearing in Single Shear and Outside Sheets of Double Shear Connections

A total of 128 single shear connection and double shear connection tests, that failed in the outside sheets, were conducted for investigating the combined hole configuration. In the single shear connections, slotted holes were provided in one sheet while the other sheet had an oversized hole. In the double shear connections, the slotted holes were provided in the outside sheets while the inside sheet had an oversized hole.

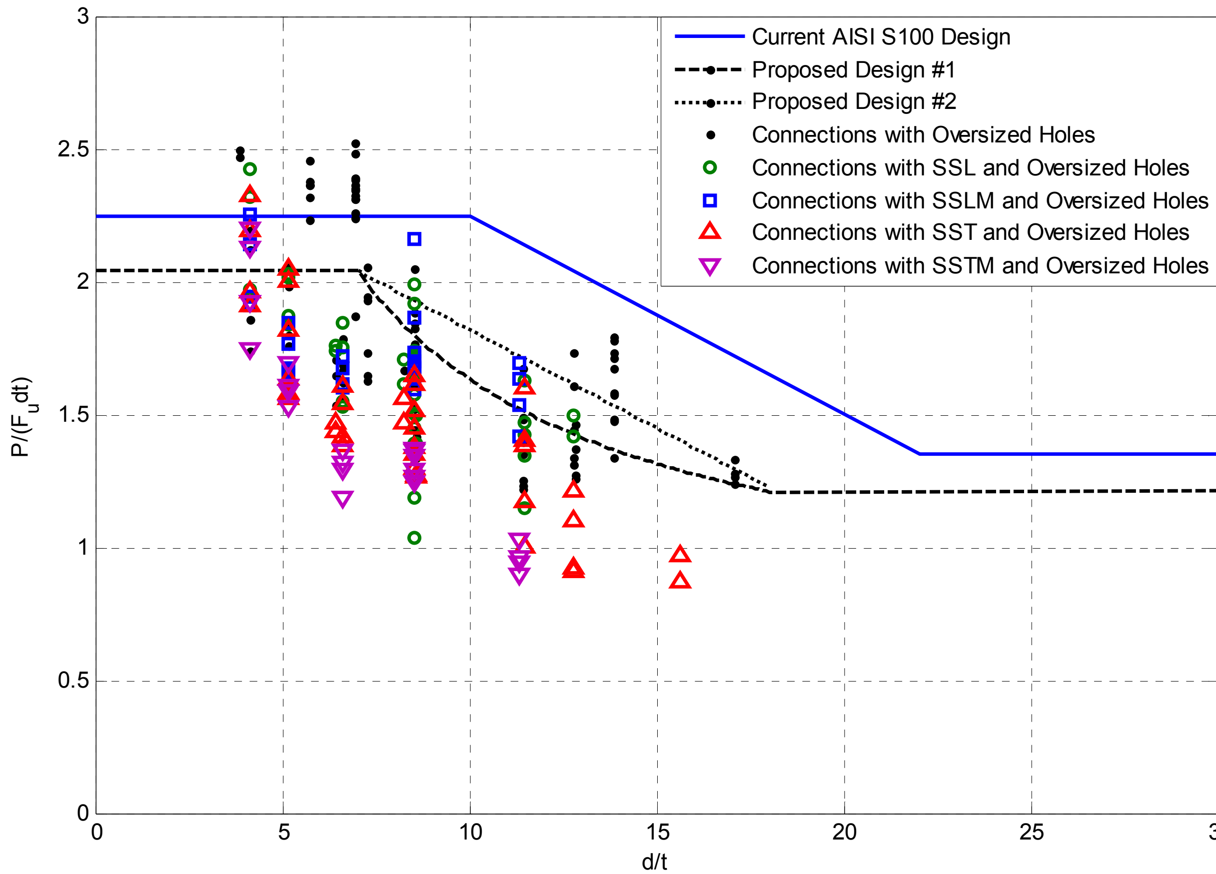

Fig 6.9 Test Results vs. Design Methods for Bearing Strength of Single Shear and Outside Sheets of Double Shear Connections

Fig 6.9 illustrates the comparison between the test results and design methods. The connections with slots parallel to the loading direction (SSL and SSLM) give similar peak loads compared to the results from the oversized hole tests. The majority of the SSL and SSLM data points in the figure are within the bounds of the data set for connections using oversized holes. The connections using slots transverse to the loading direction (SST and SSTM) yield consistently lower bearing strength values than those with SSL or SSLM slots because the SST and SSTM slots provide more gap room for the bolt head and nut to rotate and go through the holes. On average the connections with SSL or SSLM holes give 18% higher bearing strength than those with SST or SSTM holes.

The MBMA slots have a slightly longer length than the AISI short slots (see details in Table 4-1), which limits the bolt rotation to some degree and thus potentially increases the bearing strength. The SSL and SSLM configurations give similar test-to-predicted ratios, 0.77 vs. 0.78 for the AISI S100 prediction. The SST yields slightly higher strength on average, 0.67 vs. 0.63 for the AISI S100 prediction.

Overall the AISI S100 design provisions are non-conservative for the bearing strength of connections using combined oversized and slotted holes. The proposed new design methods work fairly well for those connections with oversized holes and SSL or SSLM slots. Table 6-13 summarizes the test-to-predicted ratios for single shear connections and double shear connections failing in outside sheets. The test-to-predicted ratios for SSL and SSLM configurations are 0.93 and 0.89 for the new methods #1 and #2 respectively. The ratios for SST and SSTM configurations are 0.79 and 0.75 respectively for the new methods #1 and #2. Tables 6-13 and 6-14 list the resistance factors and safety factors for parallel (SSL and SSLM) and transverse (SST and SSTM) slot configurations respectively. It is recommended that the proposed design methods can be applicable for the bearing single shear and outside sheets of double shear connections with oversized and SSL or SSLM slotted holes. The new methods may also be used for connections with oversized and SST and SSTM connections. However, the computed lower resistance factors and higher safety factors should be adopted to account for the reduction of strength.

Table 6-12 Test-to-Predicted Ratios for Sheet Bearing Strength of Single Shear Connections and Outside Sheets of Double Shear Connection with Slotted Holes

Hole config.	No. of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW1}			P_{test}/P_{NEW2}		
		Average	Std. dev.	COV	Average	Std. dev.	COV	Average	Std. dev.	COV
SSL	37	0.77	0.11	0.139	0.93	0.11	0.113	0.88	0.11	0.119
SSLM	25	0.78	0.08	0.108	0.94	0.11	0.115	0.90	0.09	0.101
SSL+SSLM	62	0.77	0.10	0.127	0.93	0.11	0.113	0.89	0.10	0.112
SST	42	0.67	0.14	0.205	0.81	0.12	0.153	0.77	0.13	0.170
SSTM	24	0.63	0.15	0.244	0.74	0.13	0.181	0.71	0.15	0.211
SST+SSTM	66	0.65	0.14	0.219	0.79	0.13	0.167	0.75	0.14	0.188
Overall	128	0.71	0.14	0.193	0.86	0.14	0.164	0.82	0.14	0.172

Table 6-13 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized and SSL or SSLM Holes without Washers

	Single shear and outside sheets of double shear connections using oversized and SSL or SSLM holes without washers		
	New method #1	New method #2	
Quantity	62	62	
Mean	0.93	0.89	
Std. Dev.	0.10	0.11	
COV	0.113	0.112	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	0.93	0.89	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.63	0.60	0.60
ϕ (LSD)	0.52	0.50	0.50
Ω (ASD)	2.43	2.53	2.50

Table 6-14 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Single Shear and Outside Sheets of Double Shear Connections Using Oversized and SST or SSTM Holes without Washers

	Single shear and outside sheets of double shear connections using oversized and SST or SSTM holes without washers		
	New method #1	New method #2	
Quantity	66	66	
Mean	0.79	0.75	
Std. Dev.	0.13	0.14	
COV	0.167	0.188	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	0.79	0.75	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.48	0.44	0.60
ϕ (LSD)	0.39	0.35	0.50
Ω (ASD)	3.17	3.49	2.50

6.1.3.2 Bearing in Inside Sheets of Double Shear Connections

A total of 36 double shear connections with oversized and slotted holes failed by bearing in the inside sheet. The AISI S100 (2007) gives an average of 28% non-conservative predictions. Fig 6.10 illustrates the comparison between the test results and design methods for the bearing strength of the inside sheet of double shear connections. The proposed design methods have a fairly reasonable match to the test results of connections using oversized and slotted holes. Since the bearing failure occurs in the oversized hole in the inside sheet, the different slot configurations in the outside sheets do not affect the bearing strength of the connections. Therefore, the 36 test results are treated equally as double shear connections using oversized holes or oversized and standard holes. A comprehensive analysis is provided in Section 6.1.4.

Table 6-15 summarizes the details of test-to-predicted ratios. Table 6-16 lists the computed resistance factors and safety factors based on the 36 tests.

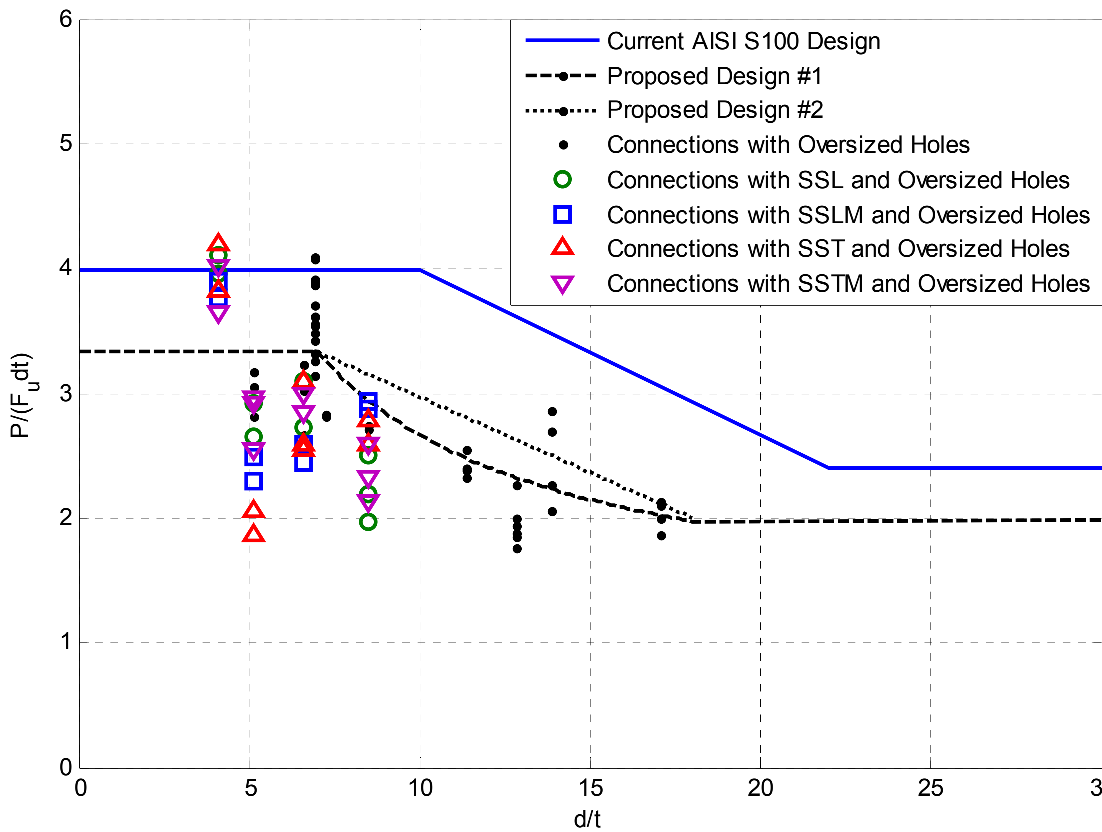

Fig 6.10 Test Results vs. Design Methods for Bearing Strength of Inside Sheet of Double Shear Connections

Table 6-15 Test-to-Predicted Ratios for Sheet Bearing Strength of Inside Sheet of Double Shear Connections with Slotted Holes

Hole config.	No. of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW1}			P_{test}/P_{NEW2}		
		Average	Std. dev.	COV	Average	Std. dev.	COV	Average	Std. dev.	COV
SSL	9	0.73	0.18	0.252	0.90	0.19	0.212	0.88	0.21	0.211
SSLM	8	0.73	0.15	0.211	0.90	0.19	0.210	0.89	0.18	0.207
SST	9	0.71	0.19	0.268	0.88	0.23	0.261	0.86	0.23	0.264
SSTM	10	0.73	0.15	0.201	0.90	0.15	0.165	0.88	0.16	0.181
Overall	36	0.72	0.16	0.224	0.89	0.18	0.204	0.88	0.19	0.213

Table 6-16 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Inside Sheet of Double Shear Connections Using Oversized and Slotted Holes without Washers

	Inside sheet of double shear connections using oversized and Slotted holes without washers		
	New method #1	New method #2	
Quantity	36	36	
Mean	0.89	0.88	
Std. Dev.	0.18	0.19	
COV	0.204	0.213	
M_m	1.10	1.10	
V_m	0.08	0.08	
F_m	1.00	1.00	
P_m	0.89	0.88	
V_f	0.05	0.05	
β (LRFD)	3.5	3.5	
β (LSD)	4.0	4.0	
V_Q	0.21	0.21	AISI S100
ϕ (LRFD)	0.50	0.48	0.60
ϕ (LSD)	0.40	0.38	0.50
Ω (ASD)	3.09	3.19	2.50

6.1.4 Overall Analysis and Summary of Proposed Provisions for Sheet Bearing Strength of Bolted Connections Using Oversized and Slotted Holes without Washers

6.1.4.1 Bearing in Single Shear and Outside Sheets of Double Shear Connections

The discussions in previous sections have come to the conclusion that the tested connection configurations can be divided into two groups for determining the nominal bearing strength of single shear and outside sheets of double shear connections: (1) connections using oversized holes, oversized and standard hole, oversized and SSL or SSLM slots; (2) connections using oversized and SST or SSTM slots. In each group, the various connection configurations show similar behavior and peak loads in tests. Table 6-17 summarizes the test-to-predicted ratios for those two groups of connection configurations. The proposed two new methods for bearing are applicable to those two groups of connections, but each group uses the specified resistance factors and safety factor as listed in Table 6-18.

Table 6-17 Test-to-Predicted Ratios for Sheet Bearing Strength of Single Shear Connections and Outside Sheets of Double Shear Connections

Connection type	No. of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW1}			P_{test}/P_{NEW2}		
		Avg.	Std. dev.	COV	Avg.	Std. dev.	COV	Average	Std. dev.	COV
Group 1	187	0.79	0.13	0.166	0.97	0.13	0.138	0.92	0.13	0.144
Group 2	66	0.65	0.14	0.219	0.79	0.13	0.167	0.75	0.14	0.188

Table 6-18 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Single Shear and Outside Sheets of Double Shear Connections

	Group 1		Group 2	
	New method #1	New method #2	New method #1	New method #2
Quantity	187	187	66	66
Mean	0.97	0.92	0.79	0.75
Std. Dev.	0.13	0.13	0.13	0.14
COV	0.138	0.144	0.167	0.188
M_m	1.10	1.10	1.10	1.10
V_m	0.08	0.08	0.08	0.08
F_m	1.00	1.00	1.00	1.00
P_m	0.97	0.92	0.79	0.75
V_f	0.05	0.05	0.05	0.05
β (LRFD)	3.5	3.5	3.5	3.5
β (LSD)	4.0	4.0	4.0	4.0
V_Q	0.21	0.21	0.21	0.21
ϕ (LRFD)	0.63	0.59	0.48	0.44
ϕ (LSD)	0.52	0.48	0.39	0.35
Ω (ASD)	2.42	2.58	3.17	3.49

6.1.4.2 Bearing in Inside Sheets of Double Shear Connections

Since all the double shear connections used an oversized hole in the inside sheet, the bearing strength of the inside sheet can be analyzed for connections with all hole configurations including oversized holes, oversized and standard holes, oversized and slotted holes. A total of 91 double shear connections in both Phases 1 and 2 failed by bearing in the inside sheet. The test-to-predicted ratios are listed in Table 6-19.

Table 6-19 Test-to-Predicted Ratios for Sheet Bearing Strength of Single Shear Connections and Outside Sheets of Double Shear Connections

No. of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW1}			P_{test}/P_{NEW2}		
	Avg.	Std. dev.	COV	Avg.	Std. dev.	COV	Avg.	Std. dev.	COV
91	0.75	0.15	0.205	0.96	0.16	0.167	0.93	0.17	0.179

Table 6-20 lists the computed resistance factors and safety factors for the proposed new bearing methods to be used for determining the nominal bearing strength of the inside sheet of double shear connections using oversized holes or oversized holes combined with standard or slotted holes.

Table 6-20 Resistance Factors and Safety Factors for Proposed Design Methods for Bearing in Inside Sheet of Double Shear Bolted Connections

	New method #1	New method #2
Quantity	91	91
Mean	0.96	0.93
Std. Dev.	0.16	0.17
COV	0.167	0.179
M_m	1.10	1.10
V_m	0.08	0.08
F_m	1.00	1.00
P_m	0.96	0.93
V_f	0.05	0.05
β (LRFD)	3.5	3.5
β (LSD)	4.0	4.0
V_Q	0.21	0.21
ϕ (LRFD)	0.59	0.56
ϕ (LSD)	0.48	0.45
Ω (ASD)	2.59	2.75

6.1.4.3 Summary of Proposed Design Provision for Bearing

<u>(A) Main Method</u>

The following provisions are proposed to add to the section E3.3.1 of AISI S100 (2007)

When oversized or slotted holes are used in bolted connections without using washers, the nominal bearing strength [resistance], P_n, of the connected sheet for each loaded bolt shall be determined in accordance with the following provisions.

$$P_n = C\, m_f\, d\, t\, F_u$$

For bearing of single shear and outside sheets of double shear connections using oversized holes or a combination of oversized holes with standard holes, AISI short-slot holes, or MBMA slotted holes, the slots shall be parallel to the applied load.

Ω = 2.42 (ASD)

ϕ = 0.63 (LRFD)

= 0.52 (LSD)

For bearing of single shear and outside sheets of double shear connections using oversized and AISI short-slot holes or MBMA slotted holes, the slots shall be transverse to the applied load.

Ω = 3.17 (ASD)

ϕ = 0.48 (LRFD)

= 0.39 (LSD)

For bearing of the inside sheet of double shear connections using an oversized hole in the inside sheet.

Ω = 2.59 (ASD)

ϕ = 0.59 (LRFD)

= 0.48 (LSD)

where

C = Bearing factor, determined in accordance with Table 6-21

m_f = Modification factor for type of bearing connection, which shall be determined according to Table 6-22

d = Nominal bolt diameter

t = Uncoated sheet thickness

F_u = Tensile strength of sheet

Table 6-21 Bearing Factor, C

Thickness of connected part, t, in. (mm)	Ratio of fastener diameter to member thickness, d/t	C
$0.024 \le t < 0.1875$ ($0.61 \le t < 4.76$)	$d/t < 7$	3
	$7 \le d/t \le 18$	$1+14/(d/t)$
	$d/t > 18$	1.8

Table 6-22 Modification Factor, m_f, for Type of Bearing Connection

Type of bearing connection	m_f
Single shear and outside sheets of double shear connection without washers under both bolt head and nut on oversized hole	0.68
Inside sheet of double shear connection without washers on oversized hole	1.11

(B) Alternative Method

The following provisions are for the alternative bearing strength.

When oversized or slotted holes are used in bolted connections without using washers, the nominal bearing strength [resistance], P_n, of the connected sheet for each loaded bolt shall be determined in accordance with the following provisions.

$$P_n = C\, m_f\, d\, t\, F_u$$

For bearing of single shear and outside sheets of double shear connections using oversized holes or a combination of oversized holes with standard holes, AISI short-slot holes, or MBMA slotted holes, the slots shall be parallel to the applied load.

$\Omega = 2.58$ (ASD)

$\phi = 0.59$ (LRFD)

$= 0.48$ (LSD)

For bearing of single shear and outside sheets of double shear connections using oversized and AISI short-slot holes or MBMA slotted holes, the slots shall be transverse to the applied load.

Ω = 3.49 (ASD)

ϕ = 0.44 (LRFD)

= 0.35 (LSD)

For bearing of inside sheet of double shear connection using oversized hole on inside sheet.

Ω = 2.75 (ASD)

ϕ = 0.56 (LRFD)

= 0.45 (LSD)

where

C = Bearing factor, determined in accordance with Table 6-23

m_f = Modification factor for type of bearing connection, which shall be determined according to Table 6-22

d = Nominal bolt diameter

t = Uncoated sheet thickness

F_u = Tensile strength of sheet

Table 6-23 Bearing Factor, C

Thickness of connected part, t, in. (mm)	Ratio of fastener diameter to member thickness, d/t	C
0.024 ≤ t < 0.1875 (0.61 ≤ t < 4.76)	d/t < 7	3
	7 ≤ d/t ≤ 18	3.762-0.109(d/t)
	d/t > 18	1.8

6.2 SHEET SHEAR STRENGTH

6.2.1 Sheet Shear Strength of Bolted Connections Using Oversized Holes without Washers

A total of 76 single shear and double shear connections using oversized holes without washers were conducted in both Phases 1 and 2 to evaluate the shear resistance of the sheet affected by the edge distance in the direction of applied load. Among the 76 tests, 9 tests used low-ductility materials. The test results are compared with the nominal shear strength determined by both the U.S. provisions and the Canadian provisions of AISI S100 (2007). The test-to-predicted ratios for those two provisions for each test are respectively listed as P_{test}/P_{NAS_US} and P_{test}/P_{NAS_CAN} in the Appendix Tables A-13 through A-15.

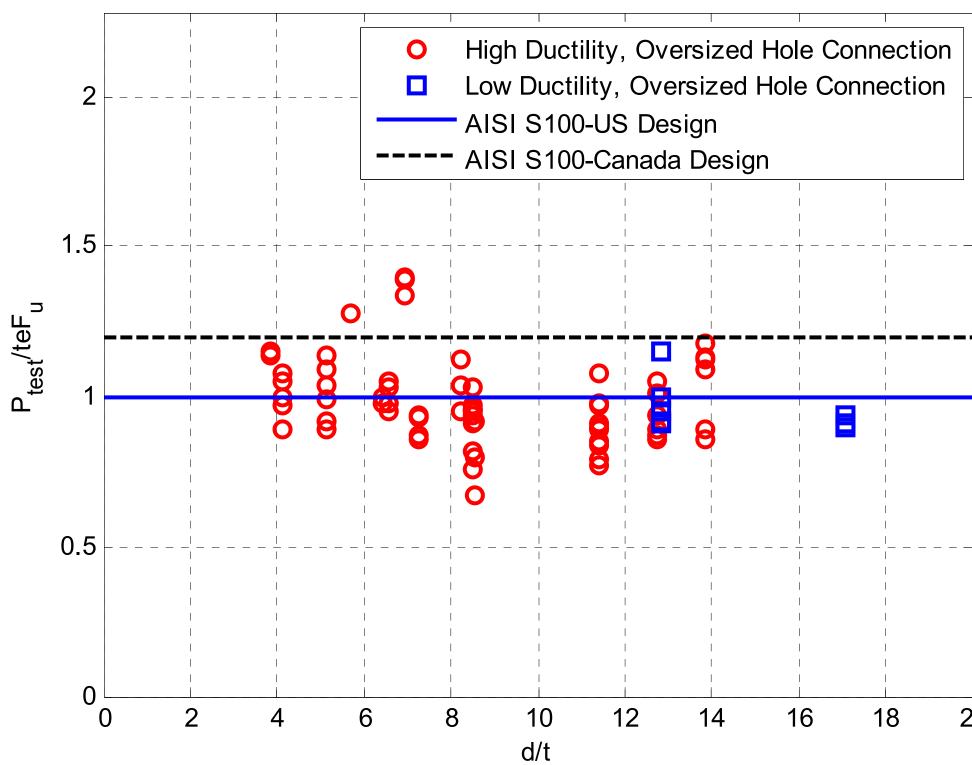

Fig 6.11 Comparison of Test Results with AISI S100 Predictions for Sheet Shear Strength of Connections with Oversized Holes

Fig 6.11 illustrates a comparison of the test results with the AISI S100 (2007) predictions. The figure indicates that the high ductility steel connections yield similar test-to-predicted ratios to those of lower ductility steel connections using the actual tensile strength in the calculations. The U.S. provisions have a good agreement with the test results. The average ratio of P_{test}/P_{NAS_US} for the high ductility steel sheets is 0.99 with a standard deviation of 0.15. For the low ductility steel sheets, the P_{test}/P_{NAS_US} ratio is 0.95 with a standard deviation of 0.08. The Canadian provisions for the tested connection configurations systematically had a 20% higher nominal strength than from the U.S. provisions. The test-to-predicted ratios for the Canadian provisions are 0.78 and 0.76 for the high and low ductility steels respectively.

No significant difference is found between the single and double shear connections in terms of the sheet shear strength. The detailed statistical results for the test-to-predicted ratios are listed in Table 6-24.

Table 6-24 Test-to-Predicted Ratios for Sheet Shear Strength of Connections with Oversized Holes

Connection configuration	No. of tests	P_{test}/P_{NAS-US}			$P_{test}/P_{NAS-CAN}$		
		Avg.	Std. dev.	COV	Avg.	Std. dev.	COV
Single shear and outside sheets of double shear	46	0.99	0.15	0.150	0.78	0.12	0.152
Inside sheet of double shear	30	0.98	0.14	0.145	0.78	0.09	0.115
High ductility steel	67	0.99	0.15	0.153	0.78	0.11	0.143
Low ductility steel	9	0.95	0.08	0.084	0.76	0.06	0.085
Overall	76	0.99	0.15	0.147	0.78	0.107	0.137

The AISI S100 (2007) U.S. provisions use different safety factors and resistance factors for materials with different ductility. Based on the test results, the ASD safety factor and resistance factors for LRFD and LSD are calculated using the method previously described in Section 6.1.1.1. The results are listed in Table 6-25. Due to the large variation in the test results for the high ductility steel, the computed safety factors and resistance factors are more conservative than the values in AISI S100 (2007). The calculated LRFD resistance factor for the low ductility steel is higher than the AISI S100 value. However the number of tests using low ductility steel is relatively small and only two sheet thicknesses are included in the test matrix. Further tests are needed to address the shear strength of low ductility steel. The test results indicate that the U.S. provisions of AISI S100 for shear strength are appropriate for connections using oversized holes without washers, while specific resistance factors and the ASD safety factor shall be used for those tested configurations. The Canadian provisions of AISI S100 give approximately a 20% non-conservative predication for the nominal shear strength, therefore it is recommended to use the U.S. provisions as the unified design method for nominal shear strength of connected sheets affected by edge distance.

Table 6-25 Resistance Factors and Safety Factors for Design Methods for Sheet Shear Strength of Single Shear and Outside Sheets of Double Shear Connections Using Oversized Holes without Washers – AISI S100 U.S. Provisions

		High ductility $F_u/F_y \geq 1.08$	Low ductility $F_u/F_y < 1.08$
Quantity		67	9
Mean		0.99	0.95
Std. Dev.		0.15	0.08
COV		0.153	0.084
M_m		1.10	1.10
V_m		0.08	0.08
F_m		1.00	1.00
P_m		0.99	0.95
V_f		0.05	0.05
β (LRFD)		3.5	3.5
β (LSD)		4.0	4.0
V_Q		0.21	0.21
Tests	ϕ (LRFD)	0.62	0.66
	ϕ (LSD)	0.51	0.54
	Ω (ASD)	2.45	2.33
AISI S100	ϕ (LRFD)	0.70	0.60
	ϕ (LSD)	0.75	0.75
	Ω (ASD)	2.00	2.22

6.2.2 Sheet Shear Strength of Bolted Connections Using Oversized and Standard Holes without Washers

A total of 34 bolted connections with oversized and standard holes that were tested in this research had shear failures. All tests were done in Phase 2 using high ductility steel. The test results are compared with both the U.S. provisions and the Canadian provisions of AISI S100 (2007). Fig 6.12 shows the comparison of test results with AISI S100 provisions. The U.S. provisions have a good agreement with the tested shear strength; the average test-to-predicted ratio is 0.96 with a standard deviation 0.12. The Canadian provisions in AISI S100, on the other hand, had an average 19% non-conservative prediction for the nominal shear strength. Table 6-26 lists the test-to-predicted ratios.

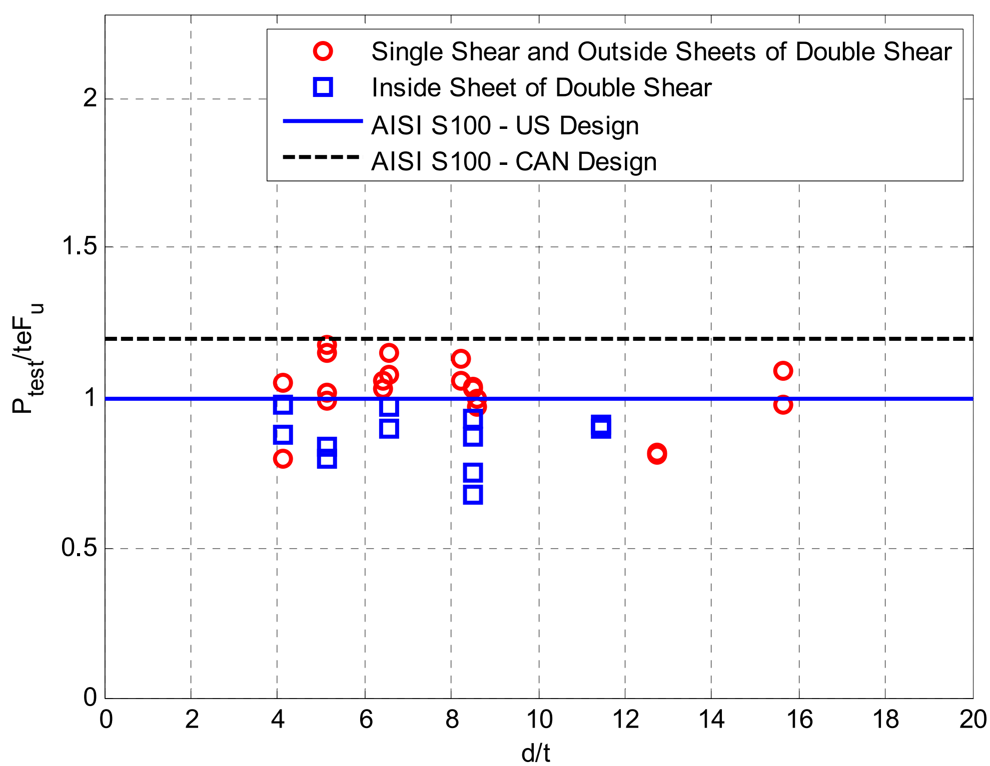

Fig 6.12 Comparison of Test Results with AISI S100 Predictions for Sheet Shear Strength of Connections with Oversized and Standard Holes

Table 6-27 lists the calculated resistance factors and safety factor for the sheet shear strength of connections using oversized and standard holes without washers. Since the inside sheet of the double shear connections has an oversized hole, the design factors are computed based on tests of single shear and outside sheets of double shear connections. The results show that the calculated factors are close to and slightly better than those factors for connections with only oversized holes.

Table 6-26 Test-to-Predicted Ratios for Sheet Shearing Strength for Connections with Oversized and Standard Holes

Connection configuration	No. of tests	P_{test}/P_{NAS_US}			P_{test}/P_{NAS_CAN}		
		Avg.	Std. dev.	COV	Avg.	Std dev.	COV
Single shear and outside sheets of double shear	20	1.02	0.11	0.106	0.86	0.09	0.103
Inside sheet of double shear	14	0.87	0.08	0.094	0.73	0.06	0.079
Overall	34	0.96	0.12	0.127	0.81	0.10	0.123

Table 6-27 Resistance Factors and Safety Factors for Design Method for Sheet Shear Strength of Single Shear and Outside Sheets of Double Shear Connections Using Oversized and Standard Holes without Washers– AISI S100 U.S. Provisions

		High ductility $F_u/F_y \geq 1.08$
Quantity		20
Mean		1.02
Std. Dev.		0.11
COV		0.106
M_m		1.10
V_m		0.08
F_m		1.00
P_m		1.02
V_f		0.05
β (LRFD)		3.5
β (LSD)		4.0
V_Q		0.21
Tests	ϕ (LRFD)	0.69
	ϕ (LSD)	0.60
	Ω (ASD)	2.21
AISI S100	ϕ (LRFD)	0.70
	ϕ (LSD)	0.75
	Ω (ASD)	2.00

6.2.3 Sheet Shear Strength of Bolted Connections Using Oversized and Slotted Holes without Washers

A total of 131 high ductility steel single shear and double shear connections using oversized and slotted holes were tested to investigate the shear strength of the sheets. Fig 6.13 shows the comparison between the tested shear strength and the AISI S100 predictions. For single shear connections and the double shear connections failing in the outside sheets, the tested shear strength is lower than the AISI S100 predictions using both the U.S. and Canadian provisions. The average test-to-predicted ratio is 0.84 for the U.S. provisions and 0.71 for the Canadian provisions. All the tested shear strength of the inside sheet of double shear connections will be analyzed together due to the fact that the inside sheet always has an oversized hole. The comprehensive analysis is provided in Section 6.2.4.

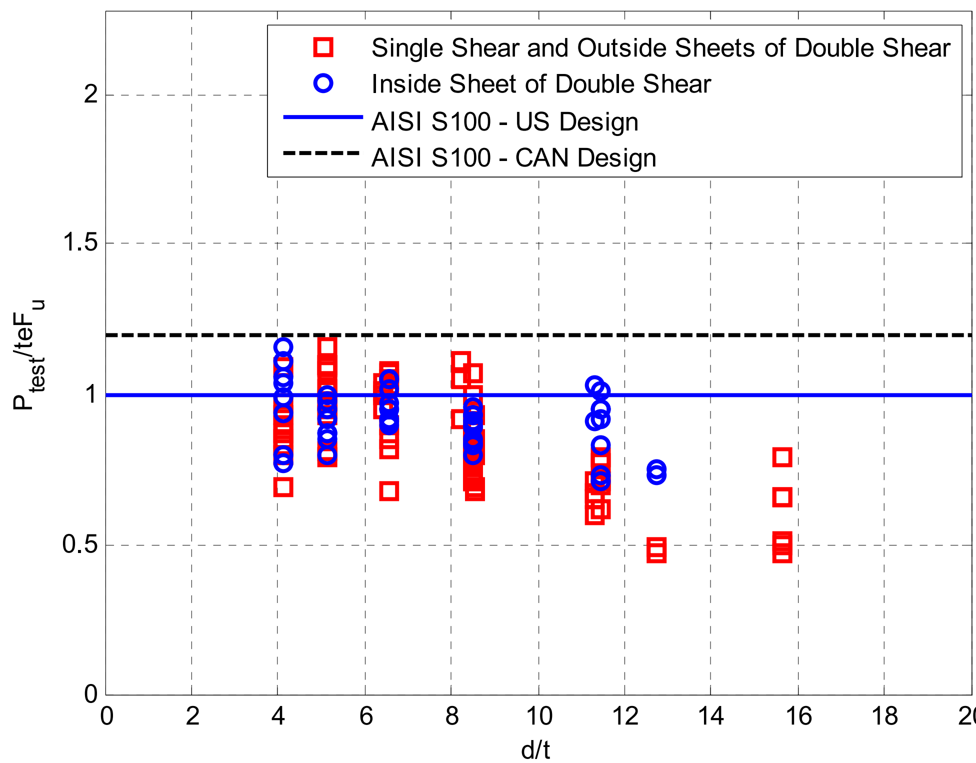

Fig 6.13 Comparison of Test Results with AISI S100 Predictions for Sheet Shear Strength of Connections with Oversized and Slotted Holes

Table 6-28 lists the detailed test-to-prediction ratios for the connections using oversized and slotted holes. For the single shear and outside sheets of double shear connections, the tests with SST and SSTM holes yield lower average test-to-predicted ratios than the tests with SSL and SSLM holes. The SST and SSTM holes have more room for the bolt to rotate and go through the sheets during the test, which results in lower strength. However, the net shear path in the sheets with SST and SSTM holes is consistently longer than the sheets with SSL and SSLM holes, and therefore the shear strength difference among the two slot orientations is not considerably large. The tested difference between SST and SSL configurations is 10% on average, and the tested difference between SSTM and SSLM configurations is on average 13% for single shear and outside sheets of double shear connections. The influence of the slot orientation to the shear strength can be neglected in determining the shear strength of sheets.

Table 6-28 Test-to-Predicted Ratios for Sheet Shear Strength of Connections with Slotted Holes

Connection configuration	No. of tests	P_{test}/P_{NAS_US}			P_{test}/P_{NAS_CAN}		
		Avg.	Std. dev.	COV	Avg.	Std. dev.	COV
SSL single shear and outside sheets of double shear	28	0.91	0.17	0.191	0.77	0.14	0.185
SSL inside sheet of double shear	14	0.88	0.07	0.067	0.74	0.09	0.124
SSLM single shear and outside sheets of double shear	15	0.84	0.13	0.159	0.70	0.11	0.156
SSLM inside sheet of double shear	11	0.99	0.07	0.067	0.82	0.05	0.066
SST single shear and outside sheets of double shear	25	0.82	0.18	0.222	0.69	0.15	0.221
SST inside sheet of double shear	13	0.89	0.10	0.117	0.75	0.08	0.106
SSTM single shear and outside sheets of double shear	15	0.73	0.07	0.091	0.62	0.06	0.091
SSTM inside sheet of double shear	10	0.94	0.10	0.107	0.80	0.10	0.128
Single Shear and Outside Sheets of Double Shear	83	0.84	0.17	0.198	0.71	0.14	0.196
Inside Sheet of Double Shear	48	0.92	0.10	0.110	0.77	0.09	0.115
Overall	131	0.87	0.15	0.174	0.73	0.13	0.173

Table 6-29 summarizes the computed resistance factors and the safety factors for single shear and outside sheets of double shear connections, since an oversized hole is used in the inside sheet of double shear connections.

Table 6-29 Resistance Factors and Safety Factors for Sheet Shear Strength of Single Shear and Outside Sheets of Double Shear Connections Using Oversized and Slotted Holes without Washers - AISI S100 U.S. Provisions

		High ductility $F_u/F_y \geq 1.08$
Quantity		83
Mean		0.84
Std. Dev.		0.11
COV		0.198
M_m		1.10
V_m		0.08
F_m		1.00
P_m		0.84
V_f		0.05
β (LRFD)		3.5
β (LSD)		4.0
V_Q		0.21
Tests	ϕ (LRFD)	0.48
	ϕ (LSD)	0.39
	Ω (ASD)	3.19
AISI S100	ϕ (LRFD)	0.70
	ϕ (LSD)	0.75
	Ω (ASD)	2.00

6.2.4 Overall Analysis and Summary of Proposed Provisions for Shear Strength of Connected Part in Bolted Connections Using Oversized and Slotted Holes without Washers

The test results indicate that the current design equations in AISI S100 U.S. provisions give reasonable predictions of the shear strength of connected sheets having oversized holes. The Canadian provisions, meanwhile, show a 20% systematically higher prediction than the U.S. provisions. It is recommended that the U.S. provisions be adopted as the unified design approach for the nominal shear strength of connected sheets in bolted connections using oversized and slotted holes without washers.

6.2.4.1 Single Shear and Outside Sheets of Double Shear Connections

The test results indicate that hole configurations affect the shear strength of the connected parts in single shear connections. It is decided to adopt the following resistance factors and safety factor for different hole configurations. The following provisions are proposed to be added to Appendix A Section E3.1 for Eq. E3.1-1 of AISI

S100 (2007).

(c) When $F_u/F_{sy} \geq 1.08$, single shear or outside sheets of double shear connections using only oversized holes without washers,

Ω = 2.45 (ASD)

ϕ = 0.62 (LRFD)

= 0.51 (LSD)

(d) When $F_u/F_{sy} \geq 1.08$, single shear or outside sheets of double shear connections using oversized holes and standard holes without washers,

Ω = 2.21 (ASD)

ϕ = 0.69 (LRFD)

= 0.60 (LSD)

(e) When $F_u/F_{sy} \geq 1.08$, single shear or outside sheets of double shear connections using oversized and slotted holes without washers,

Ω = 3.19 (ASD)

ϕ = 0.48 (LRFD)

= 0.39 (LSD)

6.2.4.2 Inside Sheet of Double Shear Connections

Since all double shear connections used an oversized hole in the inside sheet, the hole configurations on the outside sheets did not influence the shear strength of the inside sheet. The test results of inside sheet shear strength are summarized in Table 6-30. Table 6-31 lists the computed resistance factors and the safety factors.

Table 6-30 Test-to-Predicted Ratios for Sheet Shear Strength of Inside Sheet of Double Shear Connections

Connection configuration	No. of tests	P_{test}/P_{NAS-US}			$P_{test}/P_{NAS-CAN}$		
		Avg.	Std. dev.	COV	Avg.	Std. dev.	COV
O	30	0.98	0.14	0.145	0.78	0.09	0.115
O+S	14	0.87	0.08	0.094	0.73	0.06	0.079
O+SSL	14	0.88	0.07	0.067	0.74	0.09	0.124
O+SSLM	11	0.99	0.07	0.067	0.82	0.05	0.066
O+SST	13	0.89	0.10	0.117	0.75	0.08	0.106
O+SSTM	10	0.94	0.10	0.107	0.80	0.10	0.128
Overall	92	0.93	0.12	0.128	0.77	0.09	0.112

Table 6-31 Resistance Factors and Safety Factors for Sheet Shear Strength of Inside Sheet of Double Shear Bolted Connections – AISI S100 U.S. Provisions

		High ductility $F_u/F_y \geq 1.08$
Quantity		92
Mean		0.93
Std. Dev.		0.12
COV		0.128
M_m		1.10
V_m		0.08
F_m		1.00
P_m		0.198
V_f		0.05
β (LRFD)		3.5
β (LSD)		4.0
V_Q		0.21
Tests	ϕ (LRFD)	0.62
	ϕ (LSD)	0.50
	Ω (ASD)	2.49
AISI S100	ϕ (LRFD)	0.70
	ϕ (LSD)	0.75
	Ω (ASD)	2.00

The following provisions are proposed to be added to Appendix A, Section E3.1 for Eq. E3.1-1 of AISI S100 (2007).

(f) When $F_u/F_{sy} \geq 1.08$, inside sheet of double shear connections using oversized holes without washers,

Ω = 2.49 (ASD)

ϕ = 0.62 (LRFD)

= 0.50 (LSD)

6.3 RUPTURE IN NET SECTION OF SHEETS OF BOLTED CONNECTIONS USING OVERSIZED HOLES WITHOUT WASHERS

Rupture in the net section of sheets for CFS bolted connections using oversized and slotted holes without washers was investigated in this research. A total of 25 single shear bolted connection tests were conducted. The AISI S100 (2007) adopts two different provisions for the U.S. and Canada for determining the nominal rupture strength in the net section for bolted connections without washers. Fig 6.14 illustrates the comparison of the test results and the AISI S100 predictions. As described in Section 5.4, the connections with d/s = 0.2 demonstrated a bearing failure mode, net section rupture was not observed. Therefore, only the test results of connections with d/s = 0.4 were used to compare with the design values. Fig 6.14 indicates that the tested rupture strengths have good agreement with both the U.S. and Canadian provisions of AISI S100. Table 6-32 summarizes the test-to-predicted ratios for the two design methods.

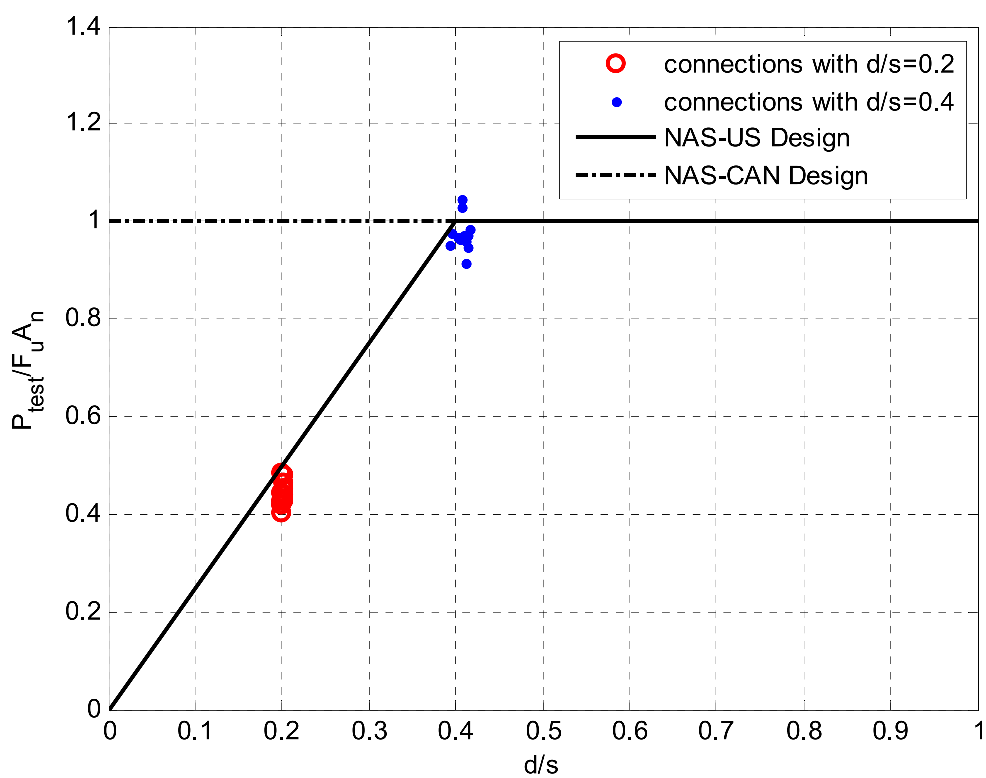

Fig 6.14 P_{test} /(F_uA_n) vs. d/s for Net Section Rupture of Tested Bolted Connections

Table 6-32 Test-to-Predicted Ratios for Rupture of Net Section of Connections Using Oversized Holes without Washers

No. of tests	P_{test}/P_{NAS_US}			P_{test}/P_{NAS_CAN}		
	Avg.	Std. dev.	COV	Avg.	Std. dev.	COV
12	0.98	0.03	0.035	0.97	0.04	0.036

Based on the 12 connections with d/s = 0.4, the ASD safety factor and resistance factors for LRFD and LSD are computed. The results are listed in Table 6-31. Compared to the resistance factors and the safety factor in AISI S100 (2007), the factors computed from the test results are close. It is recommended to use the existing design provisions in AISI S100 (2007) for the rupture in net section of bolted connections with oversized or oversized and slotted combined hole configurations without washers.

Table 6-33 Resistance Factors and Safety Factors for Design Method for Rupture in Net Section

		AISI S100 U.S. provisions	AISI S100 Canadian provisions
Quantity		12	12
Mean		0.98	0.97
Std. Dev.		0.03	0.04
COV		0.035	0.036
M_m		1.10	1.10
V_m		0.08	0.08
F_m		1.00	1.00
P_m		0.98	0.97
V_f		0.05	0.05
β (LRFD)		3.5	3.5
β (LSD)		4.0	4.0
V_Q		0.21	0.21
Tests	ϕ (LRFD)	0.70	-
	ϕ (LSD)	-	0.58
	Ω (ASD)	2.18	-
AISI S100	ϕ (LRFD)	0.65	-
	ϕ (LSD)	-	0.55
	Ω (ASD)	2.20	-

7 CONCLUSIONS

The tension tests on CFS bolted connections with oversized holes and slotted holes without using washers were conducted to investigate the connection strength of three typical failure modes - sheet shear, sheet bearing, and net section rupture. A large range of various specimen configurations were investigated in terms of the sheet thicknesses, hole dimensions, slot orientations, and connection types. Tilting of bolts and warping of sheets were observed in the single shear connection tests. In the double shear connection tests, the bolts remained perpendicular to the loading direction. Failure on both the inside sheet and the outside sheets were observed in the double shear connection tests.

The bolted connection tests exhibited significant slippage and large deformations due to the oversized hole or slotted hole dimensions in the sheets. For the connections with 1/2 in. diameter bolts, as much as 0.5 in. of initial slippage was observed in the connected sheets. Because of the large bolt deformations that occurred, it is not recommended using CFS bolted connections with oversized or slotted holes without washers for those applications where the connection deformation is a design concern.

The peak loads of the tension tests were used to evaluate the existing design provisions in AISI S100 for the nominal strength of bolted connections without consideration of deformation. The test results indicate that the current AISI S100 (2007) design equation for the sheet shear strength (U.S. provisions) works well based on the tested bolted connections. However, a large variation in the peak loads exist, which results in specific LRFD and LSD resistance factors and ASD safety factors for different hole configurations. The design equation of the Canadian provisions in AISI S100 gives systematically 20% higher predictions than the equation in the U.S. provisions. It is recommended that AISI adopt the U.S. provisions as the unified design method for the shear strength of connected sheets affected by edge distance when oversized or slotted holes are used without washers. Revised resistance factors and safety factors are proposed for various hole configurations.

For the bearing strength of sheets, the AISI S100 design method yields non-conservative predictions for the bolted connections with oversized or slotted holes. Based on the test results, two new methods are proposed to account for the reduction in the bearing strength of the tested hole configurations. The new method #1 uses non-linear functions for the bearing factor. The new method #2 adopts linear functions for the bearing factor. New modification factors are also proposed for both methods. In comparing each proposed method with the test data, the new method #1 gives better test-to-predict ratios than the new method #2. It is recommended to employ the new method #1 for determining the nominal bearing strength of bolted connections using oversized holes or an oversized hole combined with standard holes or slotted holes. The new method #2 can be used as an alternative method. Revised resistance factors and safety factors are proposed for both new methods for various hole configurations.

For the rupture failure in net section, the test results indicate that the AISI S100 design methods (both U.S. and Canadian provisions) have a good agreement with the test results. It is recommended to extend the AISI S100 design provisions for the rupture strength in net section to bolted connections using oversized or slotted holes without washers.

A limited number of connections using low-ductility steel were tested in Phase 1. It was found that the proposed methods for bearing strength work well for the low ductility steel when the full tensile strength of the steel is used in the equations. The current U.S. provisions found in AISI S100 for the sheet shear strength also work well for the tested connections using low ductility steel. However, additional tests are needed to comprehensively analyze the strength of bolted connections using low ductility steel.

The test results also indicate that connections using structural bolts (e.g. ASTM A325 bolts) yield higher bearing strength than connections using non-structural bolts (e.g. ASTM A307 Type A bolts) because of the larger head and nut sizes in the structural bolts. This research project (both Phases 1 and 2) used ASTM A307 Type A bolts for the majority of the test specimens. For a small part of test specimens, SAE Grade 8 bolts were selected to prevent failure of yielding in bolts. The proposed design methods and conclusions are applicable for connections using ASTM A325 bolts and other higher rated bolts.

8 ACKNOWLEDGEMENT

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APPENDIX – RESULTS OF PHASE 2 TESTS

Table A-1 Phase 2 Test Results for Single Shear Connections with Oversized Holes, Single Bolt, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	114O-114O-5/8-1-S-4-T1	0.1217	0.1217	Grade 8	0.625	5.14	2.48	65.7	73.1	11017	0.472	0.88	0.97	0.97
2	114O-114O-5/8-1-S-4-T2	0.1217	0.1217	Grade 8	0.625	5.14	2.49	65.7	73.1	11447	0.493	0.92	1.01	1.01
3	94O-94O-5/8-1-S-4-T1	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	9044	0.387	0.76	0.84	0.84
4	94O-94O-5/8-1-S-4-T2	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	8733	0.384	0.73	0.81	0.81
5	73O-73O-5/8-1-S-4-T1	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5863	0.489	0.74	0.91	0.85
6	73O-73O-5/8-1-S-4-T2	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5858	0.288	0.74	0.91	0.85
7	114O-114O-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	9766	0.479	0.98	1.08	1.08
8	114O-114O-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	9442	0.389	0.94	1.04	1.04
9	94O-94O-1/2-1-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7750	0.580	0.81	0.90	0.90
10	94O-94O-1/2-1-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7611	0.562	0.80	0.88	0.88
11	73O-73O-1/2-1-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.02	63.6	74.1	5028	0.295	0.79	0.88	0.88
12	73O-73O-1/2-1-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	4752	0.223	0.75	0.83	0.83
13	73O-73O-1/2-1-S-4-T3	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	4695	0.303	0.74	0.82	0.82
14	57O-57O-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.56	2.00	62.8	74.2	3326	0.332	0.68	0.85	0.79
15	57O-57O-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.56	2.00	62.8	74.2	3157	0.176	0.64	0.80	0.75
16	43O-43O-3/8-1-S-4-T1	0.0437	0.0437	A307	0.375	8.56	1.48	66.0	79.6	1754	0.140	0.60	0.75	0.70
17	43O-43O-3/8-1-S-4-T2	0.0437	0.0437	A307	0.375	8.56	1.46	66.0	79.6	1850	0.139	0.63	0.79	0.74
18	30O-30O-3/8-1-S-4-T1	0.0294	0.0294	A307	0.375	12.76	1.47	52.7	60.2	873	0.180	0.64	0.92	0.81
19	30O-30O-3/8-1-S-4-T2	0.0294	0.0294	A307	0.375	12.76	1.47	52.7	60.2	959	0.090	0.71	1.01	0.89

Table A-2 Phase 2 Test Results for Single Shear Connections with Oversized Holes, Two Bolts, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1*	114O-114O-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	7728	0.401	0.77	0.85	0.85
2*	114O-114O-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.03	65.7	73.1	8257	0.205	0.83	0.91	0.91
3*	94O-94O-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	7064	0.324	0.74	0.82	0.82
4*	94O-94O-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.02	75.3	87.3	7460	0.445	0.78	0.86	0.86
5	73O-73O-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	4569	0.385	0.72	0.80	0.80
6	73O-73O-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.01	63.6	74.1	4397	0.401	0.69	0.77	0.77
7	57O-57O-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3503	0.479	0.71	0.89	0.83
8	57O-57O-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3047	0.316	0.62	0.78	0.72

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-3 Phase 2 Test Results for Double Shear Connections with Oversized Holes, Single Bolt, e/d =4, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	43O-30O-3/8-1-D-4-T1	0.0437	0.0294	A307	0.375	12.76	1.47	52.7	60.2	1776	0.281	0.66	0.94	0.83
2	43O-30O-3/8-1-D-4-T2	0.0437	0.0294	A307	0.375	12.76	1.47	52.7	60.2	2299	0.311	0.85	1.21	1.07
3	43O-30O-3/8-1-D-4-T3	0.0437	0.0294	A307	0.375	12.76	1.47	52.7	60.2	2132	0.341	0.79	1.13	1.00
4	57O-43O-1/2-1-D-4-T1	0.0588	0.0437	A307	0.5	11.42	2.00	66.0	79.6	5163	0.549	0.69	0.98	0.86
5	57O-43O-1/2-1-D-4-T2	0.0588	0.0437	A307	0.5	11.42	2.00	66.0	79.6	4710	0.384	0.63	0.89	0.79
6	73O-43O-1/2-1-D-4-T1	0.0760	0.0437	Grade 8	0.5	11.42	2.00	66.0	79.6	5834	0.405	0.78	1.11	0.98
7	73O-43O-1/2-1-D-4-T2	0.0760	0.0437	Grade 8	0.5	11.42	2.00	66.0	79.6	5187	0.356	0.70	0.98	0.87
8	94O-57O-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	2.02	62.8	74.2	7713	0.508	0.79	0.98	0.92
9	94O-57O-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	8937	0.487	0.91	1.14	1.06
10	94O-57O-1/2-1-D-4-T3	0.0971	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	8228	0.440	0.84	1.05	0.98
11	114O-57O-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	8040	0.371	0.82	1.02	0.95
12	114O-57O-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	7973	0.483	0.81	1.02	0.95

Table A-4 Phase 2 Test Results for Double Shear Connections with Oversized Holes, Single Bolt, e/d =4, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	57O-57O-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	5906	0.561	0.68	0.92	0.86
2	57O-57O-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5989	0.526	0.69	0.93	0.87
3	73O-73O-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	7511	0.548	0.67	0.80	0.91
4	73O-73O-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	8523	0.472	0.76	0.91	0.97
5	73O-73O-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	1.98	63.6	74.1	9085	0.437	0.81	0.97	0.84
6	94O-94O-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	11909	0.527	0.70	0.84	0.92
7	94O-94O-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	12918	0.527	0.76	0.92	0.95
8	94O-94O-1/2-1-D-4-T3	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	13417	0.583	0.79	0.95	1.23
9*	114O-114O-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	18200	0.445	1.03	1.23	1.16
10*	114O-114O-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.03	65.7	73.1	17217	0.631	0.97	1.16	0.86
Note: * test performed in setup #2, the rest tests used setup #1.														

Table A-5 Phase 2 Test Results for Single Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1*	114O-114S-5/8-1-S-4-T1	0.1217	0.1217	Grade 8	0.625	5.14	2.50	65.7	73.1	12062	0.424	0.96	1.06	1.06
2*	114O-114S-5/8-1-S-4-T2	0.1217	0.1217	Grade 8	0.625	5.14	2.50	65.7	73.1	12040	0.557	0.96	1.06	1.06
3	94O-94S-5/8-1-S-4-T1	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	9463	0.435	0.79	0.88	1.09
4	94O-94S-5/8-1-S-4-T2	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	9060	0.381	0.76	0.84	1.05
5	73O-73S-5/8-1-S-4-T1	0.0760	0.0760	A307	0.625	8.22	2.49	63.6	74.1	5917	0.272	0.75	0.91	1.08
6	73O-73S-5/8-1-S-4-T2	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5898	0.274	0.74	0.91	1.07
7*	114O-114S-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.02	65.7	73.1	10532	0.463	1.05	1.16	1.16
8*	114O-114S-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	10462	0.341	1.05	1.15	1.15
9	73O-73S-1/2-1-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	5568	0.285	0.88	0.97	0.97
10	73O-73S-1/2-1-S-4-T2	0.0760	0.0760	A307	0.5	6.58	1.88	63.6	74.1	5377	0.399	0.85	0.94	0.94
11	57O-57S-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3650	0.205	0.74	0.93	0.87
12	57O-57S-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.50	1.96	62.8	74.2	3554	0.334	0.72	0.91	0.84
13	43O-43S-3/8-1-S-4-T1	0.0437	0.0437	A307	0.375	8.58	1.49	66.0	79.6	1835	0.187	0.63	0.79	0.73
14	43O-43S-3/8-1-S-4-T2	0.0437	0.0437	A307	0.375	8.58	1.50	66.0	79.6	1842	0.180	0.63	0.79	0.73
15	30O-30S-3/8-1-S-4-T1	0.0294	0.0294	A307	0.375	12.76	1.47	52.7	60.2	984	0.280	0.73	1.04	0.92
16	30O-30S-3/8-1-S-4-T2	0.0294	0.0294	A307	0.375	12.76	1.47	52.7	60.2	914	0.235	0.67	0.96	0.85

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-6 Phase 2 Test Results for Single Shear Connections with Oversized and Standard Holes, Two Bolts, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1*	114O-114S-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.03	65.7	73.1	8180	0.173	0.82	0.90	0.90
2*	114O-114S-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.02	65.7	73.1	8713	0.420	0.87	0.96	0.96
3*	94O-94S-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.02	75.3	87.3	7534	0.282	0.79	0.87	0.87
4*	94O-94S-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7220	0.464	0.76	0.84	0.84
5	73O-73S-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.02	63.6	74.1	4695	0.377	0.74	0.82	0.82
6	73O-73S-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.04	63.6	74.1	4706	0.323	0.74	0.82	0.82
7	57O-57S-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.01	62.8	74.2	3251	0.299	0.66	0.83	0.77
8	57O-57S-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.02	62.8	74.2	3294	0.354	0.67	0.84	0.78
Note: * test performed in setup #2, the rest tests used setup #1.														

Table A-7 Phase 2 Test Results for Double Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =4, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	43O-30S-3/8-1-D-4-T1	0.0437	0.0294	A307	0.375	12.76	1.44	52.7	60.2	2236	0.310	0.82	1.18	1.04
2	43O-30S-3/8-1-D-4-T2	0.0437	0.0294	A307	0.375	12.76	1.49	52.7	60.2	2328	0.367	0.86	1.23	1.09
3	57O-43S-1/2-1-D-4-T1	0.0588	0.0437	A307	0.5	11.44	1.99	66.0	79.6	4502	0.450	0.60	0.86	0.76
4	57O-43S-1/2-1-D-4-T2	0.0588	0.0437	A307	0.5	11.44	1.99	66.0	79.6	5398	0.526	0.72	1.03	0.91
5	57O-43S-1/2-1-D-4-T3	0.0588	0.0437	A307	0.5	11.44	2.00	66.0	79.6	5009	0.488	0.67	0.95	0.84
6	73O-43S-1/2-1-D-4-T1	0.0760	0.0442	A307	0.5	11.31	2.00	56.6	72.8	4123	0.369	0.60	0.84	0.74
7	73O-43S-1/2-1-D-4-T2	0.0760	0.0442	A307	0.5	11.31	1.99	56.6	72.8	3906	0.267	0.56	0.80	0.71
8	94O-57S-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	1.97	62.8	74.2	7530	0.433	0.77	0.96	0.89
9	94O-57S-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	1.97	62.8	74.2	7595	0.361	0.77	0.97	0.90
10	114O-57S-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	2.02	62.8	74.2	7452	0.480	0.76	0.95	0.89
11	114O-57S-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	7871	0.476	0.80	1.00	0.93

Table A-8 Test Results for Double Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =4, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	57O-57S-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6679	0.415	0.77	1.04	0.97
2	57O-57S-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6768	0.417	0.78	1.06	0.99
3	73O-73S-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	7739	0.636	0.69	0.83	0.83
4	73O-73S-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	8340	0.584	0.74	0.89	0.89
5*	94O-94S-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	14446	0.503	0.85	1.02	1.02
6*	94O-94S-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	15019	0.556	0.89	1.06	1.06
7*	114O-114S-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	17412	0.488	0.98	1.18	1.18
8*	114O-114S-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.02	65.7	73.1	17547	0.445	0.99	1.18	1.18

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-9 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1*	114O-114SSL-5/8-1-S-4-T1	0.1217	0.1217	Grade 8	0.625	5.14	2.50	65.7	73.1	11195	0.403	0.90	0.99	0.99
2*	114O-114SSL-5/8-1-S-4-T2	0.1217	0.1217	Grade 8	0.625	5.14	2.47	65.7	73.1	11282	0.463	0.90	0.99	0.99
3*	114O-114SST-5/8-1-S-4-T1	0.1217	0.1217	Grade 8	0.625	5.14	2.50	65.7	73.1	11407	0.472	0.91	1.01	1.01
4*	114O-114SST-5/8-1-S-4-T2	0.1217	0.1217	Grade 8	0.625	5.14	2.50	65.7	73.1	11145	0.370	0.89	0.98	0.98
5	94O-94SSL-5/8-1-S-4-T1	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	9210	0.359	0.77	0.85	0.85
6	94O-94SSL-5/8-1-S-4-T2	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	9324	0.509	0.78	0.86	0.86
7	94O-94SST-5/8-1-S-4-T1	0.0971	0.0971	A307	0.625	6.44	2.49	75.3	87.3	7625	0.277	0.64	0.71	0.71
8	94O-94SST-5/8-1-S-4-T2	0.0971	0.0971	A307	0.625	6.44	2.50	75.3	87.3	7788	0.333	0.65	0.72	0.72
9	73O-73SSL-5/8-1-S-4-T1	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	6011	0.315	0.76	0.93	0.88
10	73O-73SSL-5/8-1-S-4-T2	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5691	0.227	0.72	0.88	0.83
11	73O-73SST-5/8-1-S-4-T1	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5172	0.335	0.65	0.80	0.75
12	73O-73SST-5/8-1-S-4-T2	0.0760	0.0760	A307	0.625	8.22	2.50	63.6	74.1	5498	0.399	0.69	0.85	0.80
13*	114O-114SSL-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	10307	0.194	1.03	1.14	1.14
14*	114O-114SSL-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	10794	0.289	1.08	1.19	1.19
15*	114O-114SSLM-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	10018	0.318	1.00	1.10	1.10
16*	114O-114SSLM-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.97	65.7	73.1	9531	0.376	0.95	1.05	1.05
17*	114O-114SST-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	10342	0.521	1.03	1.14	1.14
18*	114O-114SST-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.02	65.7	73.1	9750	0.465	0.97	1.07	1.07
19*	114O-114SSTM-1/2-1-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	9800	0.484	0.98	1.08	1.08
20*	114O-114SSTM-1/2-1-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.98	65.7	73.1	9460	0.553	0.95	1.04	1.04
21	94O-94SSL-1/2-1-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	1.96	75.3	87.3	7922	0.417	0.83	0.92	0.92
22	94O-94SSL-1/2-1-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7780	0.423	0.82	0.90	0.90
23	94O-94SSLM-1/2-1-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	7479	0.519	0.78	0.87	0.86
24	94O-94SSLM-1/2-1-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	7826	0.665	0.82	0.91	0.91
25	94O-94SST-1/2-1-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7713	0.415	0.81	0.89	0.89
26	94O-94SST-1/2-1-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	6615	0.421	0.69	0.77	0.77
27	94O-94SST-1/2-1-S-4-T3	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	6609	0.435	0.69	0.76	0.76

Table A-9 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4 (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
28	94O-94SSTM-1/2-1-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	6738	0.432	0.71	0.78	0.78
29	94O-94SSTM-1/2-1-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7192	0.374	0.75	0.83	0.83
30	73O-73SSL-1/2-1-S-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	4945	0.433	0.78	0.86	0.86
31	73O-73SSL-1/2-1-S-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	2.01	63.6	74.1	5189	0.425	0.82	0.90	0.90
32	73O-73SSLM-1/2-1-S-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	4840	0.485	0.76	0.84	0.84
33	73O-73SSLM-1/2-1-S-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	4711	0.506	0.74	0.82	0.82
34	73O-73SST-1/2-1-S-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	1.98	63.6	74.1	4341	0.287	0.69	0.76	0.76
35	73O-73SST-1/2-1-S-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	4532	0.449	0.72	0.79	0.79
36	73O-73SSTM-1/2-1-S-4-T1	0.0760	0.0760	A307	0.5	6.58	1.99	63.6	74.1	3847	0.288	0.61	0.67	0.67
37	73O-73SSTM-1/2-1-S-4-T2	0.0760	0.0760	A307	0.5	6.58	1.97	63.6	74.1	3720	0.381	0.59	0.65	0.65
38	57O-57SSL-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3777	0.261	0.77	0.96	0.90
39	57O-57SSL-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.50	1.99	62.8	74.2	3796	0.377	0.77	0.97	0.90
40	57O-57SSLM-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3485	0.312	0.71	0.89	0.83
41	57O-57SSLM-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3663	0.234	0.75	0.93	0.87
42	57O-57SST-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	2837	0.417	0.58	0.72	0.67
43	57O-57SST-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3011	0.314	0.61	0.77	0.72
44	57O-57SSTM-1/2-1-S-4-T1	0.0588	0.0588	A307	0.5	8.50	1.99	62.8	74.2	2726	0.353	0.56	0.69	0.65
45	57O-57SSTM-1/2-1-S-4-T2	0.0588	0.0588	A307	0.5	8.50	1.99	62.8	74.2	2814	0.369	0.57	0.72	0.67
46	43O-43SSL-3/8-1-S-4-T1	0.0437	0.0437	A307	0.375	8.56	1.47	66.0	79.6	1817	0.273	0.62	0.78	0.72
47	43O-43SSL-3/8-1-S-4-T2	0.0437	0.0437	A307	0.375	8.56	1.48	66.0	79.6	1950	0.214	0.67	0.84	0.78
48	43O-43SST-3/8-1-S-4-T1	0.0437	0.0437	A307	0.375	8.56	1.47	66.0	79.6	1652	0.310	0.56	0.71	0.66
49	43O-43SST-3/8-1-S-4-T2	0.0437	0.0437	A307	0.375	8.56	1.46	66.0	79.6	1660	0.259	0.57	0.71	0.66
50	30O-30SSL-3/8-1-S-4-T1	0.0294	0.0294	A307	0.375	12.7	1.47	52.7	60.2	992	0.180	0.73	1.05	0.93
51	30O-30SSL-3/8-1-S-4-T2	0.0294	0.0294	A307	0.375	12.7	1.47	52.7	60.2	941	0.162	0.69	0.99	0.88
52	27O-27SST-3/8-1-S-4-T1	0.0240	0.0240	A307	0.375	15.6	1.51	50.3	57.8	452	0.058	0.46	0.65	0.62
53	27O-27SST-3/8-1-S-4-T2	0.0240	0.0240	A307	0.375	15.6	1.50	50.3	57.8	506	0.075	0.52	0.72	0.69

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-10 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Two Bolts, e/d =4

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1*	114O-114SSL-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	8751	0.369	0.87	0.96	0.96
2*	114O-114SSL-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	8643	0.298	0.86	0.95	0.95
3*	114O-114SSLM-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	8633	0.271	0.86	0.95	0.95
4*	114O-114SSLM-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	8513	0.404	0.85	0.94	0.94
5*	114O-114SST-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	8506	0.463	0.85	0.94	0.94
6*	114O-114SST-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.01	65.7	73.1	8726	0.485	0.87	0.96	0.96
7*	114O-114SSTM-1/2-2-S-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.01	65.7	73.1	7762	0.548	0.78	0.86	0.86
8*	114O-114SSTM-1/2-2-S-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	8557	0.326	0.86	0.94	0.94
9*	94O-94SSL-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7087	0.506	0.74	0.82	0.82
10*	94O-94SSL-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	1.98	75.3	87.3	7030	0.506	0.74	0.81	0.81
11*	94O-94SSLM-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7038	0.266	0.74	0.81	0.81
12*	94O-94SSLM-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	7088	0.178	0.74	0.82	0.82
13*	94O-94SST-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	6928	0.445	0.73	0.80	0.80
14*	94O-94SST-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	6718	0.388	0.70	0.78	0.78
15*	94O-94SSTM-1/2-2-S-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	6820	0.379	0.72	0.79	0.79
16*	94O-94SSTM-1/2-2-S-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	6483	0.251	0.68	0.75	0.75
17	73O-73SSL-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	4368	0.418	0.69	0.76	0.76
18	73O-73SSL-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	4314	0.422	0.68	0.75	0.75
19	73O-73SSLM-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.01	63.6	74.1	4549	0.567	0.72	0.79	0.79
20	73O-73SSLM-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.02	63.6	74.1	4511	0.576	0.71	0.79	0.79
21	73O-73SST-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	3996	0.460	0.63	0.70	0.70
22	73O-73SST-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	3905	0.331	0.62	0.68	0.68
23	73O-73SSTM-1/2-2-S-4-T1	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	3632	0.372	0.57	0.63	0.63
24	73O-73SSTM-1/2-2-S-4-T2	0.0760	0.0760	A307	0.5	6.58	2.00	63.6	74.1	3341	0.436	0.53	0.58	0.58
25	57O-57SSL-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3761	0.471	0.77	0.96	0.89
26	57O-57SSL-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	1.99	62.8	74.2	3435	0.537	0.70	0.87	0.82

Table A-10 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Two Bolts, e/d =4 (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
27	57O-57SSL-1/2-2-S-4-T3	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	75.2	3204	0.299	0.65	0.82	0.75
28	57O-57SSLM-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3487	0.594	0.71	0.89	0.83
29	57O-57SSLM-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3664	0.603	0.75	0.93	0.87
30	57O-57SST-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3042	0.262	0.62	0.77	0.72
31	57O-57SST-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	3275	0.335	0.67	0.83	0.78
32	57O-57SSTM-1/2-2-S-4-T1	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	2263	0.290	0.46	0.58	0.54
33	57O-57SSTM-1/2-2-S-4-T2	0.0588	0.0588	A307	0.5	8.50	2.00	62.8	74.2	2585	0.258	0.53	0.66	0.61

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-11 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	43O-30SST-3/8-1-D-4-T1	0.0437	0.0294	A307	0.375	12.76	1.50	52.7	60.2	1612	0.319	0.59	0.85	0.75
2	43O-30SST-3/8-1-D-4-T2	0.0437	0.0294	A307	0.375	12.76	1.51	52.7	60.2	1208	0.185	0.45	0.64	0.56
3	43O-30SST-3/8-1-D-4-T3	0.0437	0.0294	A307	0.375	12.76	1.47	52.7	60.2	1459	0.327	0.54	0.77	0.68
4	43O-30SST-3/8-1-D-4-T4	0.0437	0.0294	A307	0.375	12.76	1.50	52.7	60.2	1225	0.247	0.45	0.65	0.57
5	57O-43SSL-1/2-1-D-4-T1	0.0588	0.0437	A307	0.5	11.44	2.01	66.0	79.6	5662	0.546	0.76	1.08	0.95
6	57O-43SSL-1/2-1-D-4-T2	0.0588	0.0437	A307	0.5	11.44	1.91	66.0	79.6	3997	0.295	0.54	0.76	0.67
7	57O-43SSL-1/2-1-D-4-T3	0.0588	0.0437	A307	0.5	11.44	2.00	66.0	79.6	5116	0.287	0.69	0.97	0.86
8	57O-43SSLM-1/2-1-D-4-T1	0.0588	0.0442	Grade 8	0.5	11.31	2.00	56.6	72.8	5267	0.566	0.76	1.08	0.95
9	57O-43SSLM-1/2-1-D-4-T2	0.0588	0.0442	Grade 8	0.5	11.31	2.00	56.6	72.8	5455	0.577	0.79	1.11	0.98
10	57O-43SST-1/2-1-D-4-T1	0.0588	0.0437	Grade 8	0.5	11.44	2.00	66.0	79.6	4821	0.637	0.65	0.92	0.81
11	57O-43SST-1/2-1-D-4-T2	0.0588	0.0437	Grade 8	0.5	11.44	2.00	66.0	79.6	3485	0.260	0.47	0.66	0.59
12	57O-43SST-1/2-1-D-4-T3	0.0588	0.0437	Grade 8	0.5	11.44	2.02	66.0	79.6	3485	0.385	0.47	0.66	0.59
13	57O-43SSTM-1/2-1-D-4-T1	0.0588	0.0442	Grade 8	0.5	11.31	1.99	56.6	72.8	2892	0.272	0.42	0.59	0.52
14	57O-43SSTM-1/2-1-D-4-T2	0.0588	0.0442	Grade 8	0.5	11.31	2.00	56.6	72.8	3320	0.385	0.48	0.68	0.60
15	73O-43SSL-1/2-1-D-4-T1	0.076	0.0437	A307	0.5	11.44	2.00	66.0	79.6	4677	0.251	0.63	0.89	0.79
16	73O-43SSL-1/2-1-D-4-T2	0.076	0.0437	A307	0.5	11.44	2.00	66.0	79.6	4961	0.490	0.67	0.94	0.83
17	73O-43SSLM-1/2-1-D-4-T1	0.076	0.0442	Grade 8	0.5	11.31	1.99	56.6	72.8	4942	0.513	0.71	1.01	0.89
18	73O-43SSLM-1/2-1-D-4-T2	0.076	0.0442	Grade 8	0.5	11.31	1.99	56.6	72.8	4561	0.341	0.66	0.93	0.82
19	73O-43SST-1/2-1-D-4-T1	0.076	0.0437	Grade 8	0.5	11.44	2.00	66.0	79.6	4091	0.181	0.55	0.78	0.69
20	73O-43SST-1/2-1-D-4-T2	0.076	0.0437	Grade 8	0.5	11.44	2.01	66.0	79.6	5576	0.650	0.75	1.06	0.94
21	73O-43SST-1/2-1-D-4-T3	0.076	0.0437	Grade 8	0.5	11.44	1.99	66.0	79.6	4878	0.305	0.65	0.93	0.82
22	73O-43SSTM-1/2-1-D-4-T1	0.076	0.0442	Grade 8	0.5	11.31	1.73	56.6	72.8	3044	0.345	0.44	0.62	0.55
23	73O-43SSTM-1/2-1-D-4-T2	0.076	0.0442	Grade 8	0.5	11.31	1.99	56.6	72.8	3104	0.198	0.45	0.63	0.56
24	94O-57SSL-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	1.97	62.8	74.2	7466	0.327	0.76	0.95	0.89
25	94O-57SSL-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	8674	0.501	0.88	1.10	1.03
26	94O-57SSL-1/2-1-D-4-T3	0.0971	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	7132	0.268	0.73	0.91	0.85

Table A-11 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4, Failure in Outside Sheets (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
27	94O-57SSLM-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	1.97	62.8	74.2	7552	0.575	0.77	0.96	0.90
28	94O-57SSLM-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	2.02	62.8	74.2	9420	0.343	0.96	1.20	1.12
29	94O-57SSLM-1/2-1-D-4-T3	0.0971	0.0588	Grade 8	0.5	8.50	2.02	62.8	74.2	8129	0.485	0.83	1.04	0.97
30	94O-57SST-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	7055	0.277	0.72	0.90	0.84
31	94O-57SST-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6604	0.311	0.67	0.84	0.78
32	94O-57SSTM-1/2-1-D-4-T1	0.0971	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	5979	0.254	0.61	0.76	0.71
33	94O-57SSTM-1/2-1-D-4-T2	0.0971	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5536	0.204	0.56	0.70	0.66
34	114O-57SSL-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	7514	0.356	0.76	0.96	0.89
35	114O-57SSL-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	1.97	62.8	74.2	8354	0.718	0.85	1.06	0.99
36	114O-57SSLM-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	7313	0.347	0.74	0.93	0.87
37	114O-57SSLM-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	1.93	62.8	74.2	7412	0.421	0.75	0.94	0.88
38	114O-57SST-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	7189	0.399	0.73	0.92	0.85
39	114O-57SST-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5903	0.343	0.60	0.75	0.70
40	114O-57SST-1/2-1-D-4-T3	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6338	0.224	0.65	0.81	0.75
41	114O-57SSTM-1/2-1-D-4-T1	0.1217	0.0588	Grade 8	0.5	8.50	1.96	62.8	74.2	5970	0.442	0.61	0.76	0.71
42	114O-57SSTM-1/2-1-D-4-T2	0.1217	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5858	0.286	0.60	0.75	0.70

Table A-12 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
1	57O-57SSL-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5468	0.377	0.63	0.85	0.80
2	57O-57SSL-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.01	62.8	74.2	4287	0.313	0.49	0.67	0.62
3	57O-57SSL-1/2-1-D-4-T3	0.0588	0.0588	Grade 8	0.5	8.50	2.01	62.8	74.2	4775	0.345	0.55	0.74	0.69
4	57O-57SSLM-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6389	0.582	0.73	1.00	0.93
5	57O-57SSLM-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	6268	0.886	0.72	0.98	0.91
6	57O-57SST-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5651	0.646	0.65	0.88	0.82
7	57O-57SST-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.01	62.8	74.2	6075	0.471	0.70	0.95	0.88
8	57O-57SSTM-1/2-1-D-4-T1	0.0588	0.0588	Grade 8	0.5	8.50	1.99	62.8	74.2	4642	0.516	0.53	0.72	0.68
9	57O-57SSTM-1/2-1-D-4-T2	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5648	0.720	0.65	0.88	0.82
10	57O-57SSTM-1/2-1-D-4-T3	0.0588	0.0588	Grade 8	0.5	8.50	2.00	62.8	74.2	5068	0.575	0.58	0.79	0.74
11	73O-73SSL-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.01	63.6	74.1	8709	0.546	0.77	0.93	0.93
12	73O-73SSL-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	7689	0.432	0.68	0.82	0.82
13	73O-73SSLM-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.01	63.6	74.1	6889	0.416	0.61	0.73	0.73
14	73O-73SSLM-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	7299	0.576	0.65	0.78	0.78
15	73O-73SST-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	1.99	63.6	74.1	8703	0.528	0.77	0.93	0.93
16	73O-73SST-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	7297	0.433	0.65	0.78	0.78
17	73O-73SST-1/2-1-D-4-T3	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	7157	0.441	0.64	0.76	0.76
18	73O-73SSTM-1/2-1-D-4-T1	0.0760	0.0760	Grade 8	0.5	6.58	2.00	63.6	74.1	8027	0.524	0.71	0.86	0.86
19	73O-73SSTM-1/2-1-D-4-T2	0.0760	0.0760	Grade 8	0.5	6.58	1.96	63.6	74.1	8411	0.648	0.75	0.90	0.90
20*	94O-94SSL-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	12384	0.417	0.73	0.88	0.88
21*	94O-94SSL-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	1.98	75.3	87.3	11228	0.339	0.66	0.80	0.80
22	94O-94SSLM-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	9734	0.323	0.58	0.69	0.69
23	94O-94SSLM-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	10550	0.697	0.62	0.75	0.75
24	94O-94SST-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	8693	0.582	0.51	0.62	0.62
25	94O-94SST-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	2.01	75.3	87.3	7914	0.424	0.47	0.56	0.56
26	94O-94SSTM-1/2-1-D-4-T1	0.0971	0.0971	Grade 8	0.5	5.15	2.00	75.3	87.3	10781	0.652	0.64	0.76	0.76

Table A-12 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =4, Failure in Inside Sheet (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{new1}	P_{test}/P_{new2}
27	94O-94SSTM-1/2-1-D-4-T2	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	12536	0.644	0.74	0.89	0.89
28*	94O-94SSTM-1/2-1-D-4-T3	0.0971	0.0971	Grade 8	0.5	5.15	1.99	75.3	87.3	12368	0.531	0.73	0.88	0.88
29*	114O-114SSL-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	17626	0.556	0.99	1.19	1.19
30*	114O-114SSL-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	18240	0.660	1.03	1.23	1.23
31*	114O-114SSLM-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	1.99	65.7	73.1	16766	0.473	0.95	1.13	1.13
32*	114O-114SSLM-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	1.96	65.7	73.1	17346	0.554	0.98	1.17	1.17
33*	114O-114SST-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	18673	0.719	1.05	1.26	1.26
34*	114O-114SST-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.01	65.7	73.1	16991	0.527	0.96	1.15	1.15
35*	114O-114SSTM-1/2-1-D-4-T1	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	16250	0.536	0.92	1.10	1.10
36*	114O-114SSTM-1/2-1-D-4-T2	0.1217	0.1217	Grade 8	0.5	4.11	2.00	65.7	73.1	17842	0.683	1.01	1.20	1.20
Note: * test performed in setup #2, the rest tests used setup #1.														

Table A-13 Phase 2 Test Results for Single Shear Connections with Oversized Holes, Single Bolt, e/d =1.5

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	114O-114O-5/8-1-S-1.5-T1	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	8669	0.428	1.04	0.88
2	114O-114O-5/8-1-S-1.5-T2	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	9478	0.346	1.14	0.97
3	94O-94O-5/8-1-S-1.5-T1	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	7945	0.459	1.00	0.84
4	94O-94O-5/8-1-S-1.5-T2	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	7782	0.456	0.98	0.82
5	73O-73O-5/8-1-S-1.5-T1	0.0760	0.0760	A307	0.625	8.22	0.94	63.6	74.1	5012	0.368	0.95	0.79
6	73O-73O-5/8-1-S-1.5-T2	0.0760	0.0760	A307	0.625	8.22	0.93	63.6	74.1	5514	0.462	1.04	0.88
7	73O-73O-5/8-1-S-1.5-T3	0.0760	0.0760	A307	0.625	8.22	0.93	63.6	74.1	5919	0.505	1.12	0.94
8	114O-114O-1/2-1-S-1.5-T1	0.1217	0.1217	A307	0.5	4.11	0.72	65.7	73.1	5944	0.467	0.89	0.77
9	114O-114O-1/2-1-S-1.5-T2	0.1217	0.1217	A307	0.5	4.11	0.70	65.7	73.1	7216	0.550	1.08	0.97
10	114O-114O-1/2-1-S-1.5-T3	0.1217	0.1217	A307	0.5	4.11	0.77	65.7	73.1	6464	0.487	0.97	0.79
11	94O-94O-1/2-1-S-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.74	75.3	87.3	6282	0.443	0.99	0.83
12	94O-94O-1/2-1-S-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	6910	0.588	1.09	0.91
13	73O-73O-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4421	0.320	1.05	0.87
14	73O-73O-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.74	63.6	74.1	4344	0.320	1.03	0.87
15	57O-57O-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.74	62.8	74.2	3151	0.282	0.96	0.81
16	57O-57O-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	3373	0.262	1.03	0.86
17	43O-43O-3/8-1-S-1.5-T1	0.0437	0.0437	A307	0.375	8.56	0.53	66.0	79.6	1314	0.258	0.67	0.59
18	43O-43O-3/8-1-S-1.5-T2	0.0437	0.0437	A307	0.375	8.56	0.54	66.0	79.6	1562	0.254	0.80	0.69
19	43O-43O-3/8-1-S-1.5-T3	0.0437	0.0437	A307	0.375	8.56	0.56	66.0	79.6	1800	0.250	0.92	0.77
20	43O-43O-3/8-1-S-1.5-T4	0.0442	0.0442	A307	0.375	8.48	0.56	56.6	72.8	1491	0.178	0.82	0.69
21	43O-43O-3/8-1-S-1.5-T5	0.0442	0.0442	A307	0.375	8.48	0.56	56.6	72.8	1373	0.207	0.76	0.63
22	30O-30O-3/8-1-S-1.5-T1	0.0294	0.0294	A307	0.375	12.76	0.57	52.7	60.2	856	0.193	0.86	0.71
23	30O-30O-3/8-1-S-1.5-T2	0.0294	0.0294	A307	0.375	12.76	0.59	52.7	60.2	1046	0.334	1.05	0.83
24	30O-30O-3/8-1-S-1.5-T3	0.0294	0.0294	A307	0.375	12.76	0.59	52.7	60.2	937	0.208	0.94	0.75

Table A-14 Phase 2 Test Results for Double Shear Connections with Oversized Holes, Single Bolt, e/d =1.5, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	114O-57O-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.77	62.8	74.2	6231	0.303	0.95	0.77
2	114O-57O-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.76	62.8	74.2	6207	0.348	0.95	0.78

Table A-15 Phase 2 Test Results for Double Shear Connections with Oversized Holes, Single Bolt, e/d =1.5, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	43O-30O-3/8-1-D-1.5-T1	0.0437	0.0294	A307	0.375	12.76	0.50	62.8	79.6	1740	0.222	0.89	0.83
2	43O-30O-3/8-1-D-1.5-T2	0.0437	0.0294	A307	0.375	12.76	0.55	62.8	79.6	1973	0.333	1.01	0.86
3	43O-30O-3/8-1-D-1.5-T3	0.0437	0.0294	A307	0.375	12.76	0.54	62.8	79.6	1701	0.274	0.87	0.75
4	57O-43O-1/2-1-D-1.5-T1	0.0588	0.0437	A307	0.5	11.42	0.75	62.8	74.2	2943	0.289	0.90	0.75
5	57O-43O-1/2-1-D-1.5-T2	0.0588	0.0437	A307	0.5	11.42	0.75	62.8	74.2	2975	0.360	0.91	0.76
6	57O-57O-1/2-1-D-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	3088	0.212	0.94	0.79
7	57O-57O-1/2-1-D-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	3170	0.214	0.97	0.81
8	73O-43O-1/2-1-D-1.5-T1	0.0760	0.0437	A307	0.5	11.42	0.75	63.6	74.1	4577	0.536	1.08	0.90
9	73O-43O-1/2-1-D-1.5-T2	0.0760	0.0437	A307	0.5	11.42	0.76	63.6	74.1	3568	0.468	0.85	0.69
10	73O-43O-1/2-1-D-1.5-T3	0.0760	0.0437	A307	0.5	11.42	0.75	63.6	74.1	4075	0.416	0.97	0.80
11	73O-73O-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4132	0.387	0.98	0.82
12	73O-73O-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4024	0.391	0.95	0.79
13	94O-57O-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.72	75.3	87.3	5812	0.327	0.91	0.79
14	94O-57O-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.78	75.3	87.3	6081	0.381	0.96	0.77
15	94O-94O-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.73	75.3	87.3	5866	0.317	0.92	0.79
16	94O-94O-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.72	75.3	87.3	5640	0.301	0.89	0.77
17	114O-114O-1/2-1-D-1.5-T1	0.1217	0.1217	Grade 8	0.5	4.11	0.72	65.7	73.1	7015	0.351	1.05	0.91
18	114O-114O-1/2-1-D-1.5-T2	0.1217	0.1217	Grade 8	0.5	4.11	0.71	65.7	73.1	6605	0.212	1.00	0.87

Table A-16 Phase 2 Test Results for Single Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =1.5

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	114O-114S-5/8-1-S-1.5-	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	9834	0.647	1.18	1.00
2	114O-114S-5/8-1-S-1.5-	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	9572	0.606	1.15	0.97
3	94O-94S-5/8-1-S-1.5-T1	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	8193	0.557	1.03	0.87
4	94O-94S-5/8-1-S-1.5-T2	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	8437	0.474	1.06	0.89
5	73O-73S-5/8-1-S-1.5-T1	0.0760	0.0760	A307	0.625	8.22	0.94	63.6	74.1	5613	0.381	1.06	0.88
6	73O-73S-5/8-1-S-1.5-T2	0.0760	0.0760	A307	0.625	8.22	0.94	63.6	74.1	5981	0.487	1.13	0.94
7	114O-114S-1/2-1-S-1.5-	0.1217	0.1217	A307	0.5	4.11	0.76	65.7	73.1	5363	0.260	0.80	0.66
8	114O-114S-1/2-1-S-1.5-	0.1217	0.1217	A307	0.5	4.11	0.78	65.7	73.1	6977	0.429	1.05	0.84
9	94O-94S-1/2-1-S-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.73	75.3	87.3	6301	0.366	0.99	0.85
10	94O-94S-1/2-1-S-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	6515	0.367	1.02	0.85
11	73O-73S-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.76	63.6	74.1	4867	0.321	1.15	0.95
12	73O-73S-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4542	0.308	1.08	0.90
13	57O-57S-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.76	62.8	74.2	3377	0.336	1.03	0.85
14	57O-57S-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	3389	0.336	1.04	0.86
15	43O-43S-3/8-1-S-1.5-T1	0.0437	0.0437	A307	0.375	8.58	0.54	66.0	79.6	1955	0.286	1.00	0.87
16	43O-43S-3/8-1-S-1.5-T2	0.0437	0.0437	A307	0.375	8.58	0.55	66.0	79.6	1899	0.183	0.97	0.83
17	30O-30S-3/8-1-S-1.5-T1	0.0294	0.0294	A307	0.375	12.7	0.54	52.7	60.2	820	0.089	0.82	0.71
18	30O-30S-3/8-1-S-1.5-T2	0.0294	0.0294	A307	0.375	12.7	0.55	52.7	60.2	803	0.152	0.81	0.69

Table A-17 Phase 2 Test Results for Double Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =1.5, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	43O-27S-3/8-1-D-1.5-T1	0.0442	0.0240	A307	0.375	15.63	0.56	50.3	57.8	1562	0.292	0.98	0.84
2	43O-27S-3/8-1-D-1.5-T2	0.0442	0.0240	A307	0.375	15.63	0.56	5.03	57.8	1729	0.296	1.09	0.93

Table A-18 Phase 2 Test Results for Double Shear Connections with Oversized and Standard Holes, Single Bolt, e/d =1.5, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	57O-43S-1/2-1-D-1.5-T1	0.0588	0.0437	A307	0.5	11.44	0.75	62.8	74.2	2976	0.280	0.91	0.76
2	57O-43S-1/2-1-D-1.5-T2	0.0588	0.0437	A307	0.5	11.44	0.76	62.8	74.2	2951	0.293	0.90	0.74
3	73O-43S-1/2-1-D-1.5-T1	0.0760	0.0437	A307	0.5	11.44	0.74	63.6	74.1	3839	0.442	0.91	0.77
4	73O-43S-1/2-1-D-1.5-T2	0.0760	0.0437	A307	0.5	11.44	0.75	63.6	74.1	3785	0.338	0.90	0.75
5	73O-73S-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.77	63.6	74.1	4083	0.359	0.97	0.78
6	73O-73S-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	3801	0.265	0.90	0.75
7	94O-57S-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.72	75.3	87.3	5554	0.416	0.87	0.76
8	94O-57S-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.75	75.3	87.3	5898	0.383	0.93	0.77
9	94O-94S-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.74	75.3	87.3	5063	0.322	0.80	0.67
10	94O-94S-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	5371	0.292	0.84	0.70
11	114O-57S-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.72	65.7	73.1	4971	0.273	0.75	0.65
12	114O-57S-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.71	65.7	73.1	4553	0.253	0.68	0.60
13	114O-114S-1/2-1-D-1.5-T1	0.1217	0.1217	Grade	0.5	4.11	0.75	65.7	73.1	5895	0.417	0.88	0.74
14	114O-114S-1/2-1-D-1.5-T2	0.1217	0.1217	Grade	0.5	4.11	0.75	65.7	73.1	6510	0.382	0.98	0.81

Table A-19 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =1.5

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/ P_{NAS_US}	P_{test}/ P_{NAS_CAN}
1*	114O-114SSL-5/8-1-S-1.5-T1	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	9136	0.494	1.10	0.93
2*	114O-114SSL-5/8-1-S-1.5-T2	0.1217	0.1217	A307	0.625	5.14	0.94	65.7	73.1	9683	0.616	1.16	0.96
3*	114O-114SST-5/8-1-S-1.5-T1	0.1217	0.1217	A307	0.625	5.14	0.94	65.7	73.1	9001	0.426	1.08	0.90
4*	114O-114SST-5/8-1-S-1.5-T2	0.1217	0.1217	A307	0.625	5.14	0.92	65.7	73.1	9108	0.511	1.09	0.93
5	94O-94SSL-5/8-1-S-1.5-T1	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	8238	0.663	1.04	0.87
6	94O-94SSL-5/8-1-S-1.5-T2	0.0971	0.0971	A307	0.625	6.44	0.94	75.3	87.3	8006	0.584	1.01	0.84
7	94O-94SST-5/8-1-S-1.5-T1	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	7915	0.670	1.00	0.84
8	94O-94SST-5/8-1-S-1.5-T2	0.0971	0.0971	A307	0.625	6.44	0.93	75.3	87.3	7520	0.556	0.95	0.79
9	73O-73SSL-5/8-1-S-1.5-T1	0.0760	0.0760	A307	0.625	8.22	0.92	63.6	74.1	5570	0.559	1.05	0.90
10	73O-73SSL-5/8-1-S-1.5-T2	0.0760	0.0760	A307	0.625	8.22	0.95	63.6	74.1	5881	0.563	1.11	0.92
11	73O-73SST-5/8-1-S-1.5-T1	0.0760	0.0760	A307	0.625	8.22	0.94	63.6	74.1	4879	0.455	0.92	0.77
12	73O-73SST-5/8-1-S-1.5-T2	0.0760	0.0760	A307	0.625	8.22	0.94	63.6	74.1	4870	0.432	0.92	0.77
13	114O-114SSL-1/2-1-S-1.5-T1	0.1217	0.1217	Grade 8	0.5	4.11	0.72	65.7	73.1	6497	0.446	0.97	0.85
14	114O-114SSL-1/2-1-S-1.5-T2	0.1217	0.1217	Grade 8	0.5	4.11	0.71	65.7	73.1	5361	0.337	0.80	0.71
15	114O-114SSL-1/2-1-S-1.5-T3	0.1217	0.1217	Grade 8	0.5	4.11	0.72	65.7	73.1	7246	0.465	1.09	0.93
16	114O-114SSLM-1/2-1-S-1.5-T1	0.1217	0.1217	A307	0.5	4.11	0.75	65.7	73.1	5826	0.537	0.87	0.73
17	114O-114SSLM-1/2-1-S-1.5-T2	0.1217	0.1217	Grade 8	0.5	4.11	0.76	65.7	73.1	5517	0.416	0.83	0.68
18	114O-114SST-1/2-1-S-1.5-T1	0.1217	0.1217	Grade 8	0.5	4.11	0.73	65.7	73.1	5981	0.361	0.90	0.77
19	114O-114SST-1/2-1-S-1.5-T2	0.1217	0.1217	Grade 8	0.5	4.11	0.73	65.7	73.1	6196	0.411	0.93	0.80
20	114O-114SSTM-1/2-1-S-1.5-T1	0.1217	0.1217	Grade 8	0.5	4.11	0.67	65.7	73.1	4623	0.455	0.69	0.65
21	114O-114SSTM-1/2-1-S-1.5-T2	0.1217	0.1217	Grade 8	0.5	4.11	0.75	65.7	73.1	5699	0.484	0.85	0.71
22	94O-94SSL-1/2-1-S-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.76	75.3	87.3	7015	0.692	1.10	0.91
23	94O-94SSL-1/2-1-S-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.74	75.3	87.3	6448	0.485	1.01	0.86
24	94O-94SSLM-1/2-1-S-1.5-T1	0.0971	0.0971	Grade 8	0.5	5.15	0.75	75.3	87.3	6486	0.467	1.02	0.85
25	94O-94SSLM-1/2-1-S-1.5-T2	0.0971	0.0971	Grade 8	0.5	5.15	0.75	75.3	87.3	6252	0.528	0.98	0.82
26	94O-94SST-1/2-1-S-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	6011	0.484	0.95	0.79
27	94O-94SST-1/2-1-S-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.74	75.3	87.3	5922	0.498	0.93	0.79

Table A-19 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =1.5 (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/ P_{NAS_US}	P_{test}/ P_{NAS_CAN}
28	94O-94SSTM-1/2-1-S-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	4999	0.419	0.79	0.66
29	94O-94SSTM-1/2-1-S-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	5176	0.518	0.81	0.68
30	73O-73SSL-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4448	0.455	1.05	0.88
31	73O-73SSL-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4572	0.484	1.08	0.90
32	73O-73SSLM-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4365	0.568	1.03	0.86
33	73O-73SSLM-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4534	0.905	1.07	0.89
34	73O-73SST-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.74	63.6	74.1	3595	0.430	0.85	0.72
35	73O-73SST-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	3785	0.397	0.90	0.75
36	73O-73SSTM-1/2-1-S-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.73	63.6	74.1	3481	0.318	0.82	0.71
37	73O-73SSTM-1/2-1-S-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.73	63.6	74.1	2891	0.330	0.68	0.59
38	73O-73SSTM-1/2-1-S-1.5-T3	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	2884	0.318	0.68	0.57
39	57O-57SSL-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.73	62.8	74.2	3505	0.711	1.07	0.92
40	57O-57SSL-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.73	62.8	74.2	3273	0.514	1.00	0.86
41	57O-57SSLM-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2522	0.249	0.77	0.64
42	57O-57SSLM-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2674	0.301	0.82	0.68
43	57O-57SST-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.77	62.8	74.2	2814	0.341	0.86	0.70
44	57O-57SST-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2697	0.418	0.82	0.69
45	57O-57SSTM-1/2-1-S-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2392	0.294	0.73	0.61
46	57O-57SSTM-1/2-1-S-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2486	0.370	0.76	0.63
47	43O-43SSL-3/8-1-S-1.5-T1	0.0437	0.0437	A307	0.37	8.56	0.56	66.0	79.6	1667	0.324	0.85	0.71
48	43O-43SSL-3/8-1-S-1.5-T2	0.0437	0.0437	A307	0.37	8.56	0.56	66.0	79.6	1826	0.342	0.93	0.78
49	43O-43SST-3/8-1-S-1.5-T1	0.0437	0.0437	A307	0.37	8.56	0.55	66.0	79.6	1568	0.317	0.80	0.68
50	43O-43SST-3/8-1-S-1.5-T2	0.0437	0.0437	A307	0.37	8.56	0.55	66.0	79.6	1341	0.226	0.69	0.58
51	43O-43SST-3/8-1-S-1.5-T3	0.0437	0.0437	A307	0.37	8.56	0.55	66.0	79.6	1336	0.220	0.68	0.58
52	27O-27SSL-3/8-1-S-1.5-T1	0.0240	0.0240	A307	0.37	15.6	0.58	50.3	57.8	623	0.129	0.79	0.65
53	27O-27SSL-3/8-1-S-1.5-T2	0.0240	0.0240	A307	0.37	15.6	0.57	50.3	57.8	524	0.136	0.66	0.55
54	27O-27SSL-3/8-1-S-1.5-T3	0.0240	0.0240	A307	0.37	15.6	0.56	50.3	57.8	407	0.082	0.51	0.44

Table A-19 Phase 2 Test Results for Single Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =1.5 (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
55	27O-27SSL-3/8-1-S-1.5-T4	0.0240	0.0240	A307	0.375	15.63	0.60	50.3	57.8	524	0.034	0.66	0.52
56	27O-27SST-3/8-1-S-1.5-T1	0.0240	0.0240	A307	0.375	15.63	0.58	50.3	57.8	393	0.182	0.50	0.41
57	27O-27SST-3/8-1-S-1.5-T2	0.0240	0.0240	A307	0.375	15.63	0.56	50.3	57.8	374	0.032	0.47	0.40

Note: * test performed in setup #2, the rest tests used setup #1.

Table A-20 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =1.5, Failure in Outside Sheets

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	43O-30SST-3/8-1-D-1.5-T1	0.0437	0.0294	A307	0.375	12.76	0.55	52.7	60.2	944	0.187	0.47	0.40
2	43O-30SST-3/8-1-D-1.5-T2	0.0437	0.0294	A307	0.375	12.76	0.53	52.7	60.2	974	0.182	0.49	0.43
3	73O-43SSL-1/2-1-D-1.5-T1	0.0760	0.0437	A307	0.5	11.44	0.69	66.0	79.6	3707	0.569	0.71	0.64
4	73O-43SSL-1/2-1-D-1.5-T2	0.0760	0.0437	A307	0.5	11.44	0.67	66.0	79.6	3220	0.272	0.62	0.58
5	73O-43SSL-1/2-1-D-1.5-T3	0.0760	0.0437	A307	0.5	11.44	0.75	66.0	79.6	4113	0.412	0.79	0.66
6	73O-43SSLM-1/2-1-D-1.5-T1	0.0760	0.0442	A307	0.5	11.31	0.74	56.6	72.8	3416	0.351	0.71	0.60
7	73O-43SSLM-1/2-1-D-1.5-T2	0.0760	0.0442	A307	0.5	11.31	0.74	56.6	72.8	3144	0.289	0.65	0.55
8	73O-43SST-1/2-1-D-1.5-T1	0.0760	0.0437	A307	0.5	11.44	0.75	66.0	79.6	3995	0.526	0.77	0.63
9	73O-43SST-1/2-1-D-1.5-T2	0.0760	0.0437	A307	0.5	11.44	0.75	66.0	79.6	3652	0.314	0.70	0.58
10	73O-43SSTM-1/2-1-D-1.5-T1	0.0760	0.0442	A307	0.5	11.31	0.75	56.6	72.8	3233	0.408	0.67	0.56
11	73O-43SSTM-1/2-1-D-1.5-T2	0.0760	0.0442	A307	0.5	11.31	0.74	56.6	72.8	2880	0.361	0.60	0.50
12	94O-57SSL-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.74	62.8	74.2	5817	0.417	0.89	0.75
13	94O-57SSL-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.74	62.8	74.2	5350	0.406	0.82	0.69
14	94O-57SSLM-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.73	62.8	74.2	4784	0.351	0.73	0.63
15	94O-57SSLM-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.74	62.8	74.2	5930	0.662	0.91	0.77
16	94O-57SSLM-1/2-1-D-1.5-T3	0.0971	0.0588	A307	0.5	8.50	0.74	62.8	74.2	4751	0.543	0.73	0.61
17	94O-57SSTM-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.75	62.8	74.2	4744	0.340	0.72	0.60
18	94O-57SSTM-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.73	62.8	74.2	4623	0.376	0.71	0.60
19	114O-57SSL-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.72	62.8	74.2	5619	0.371	0.86	0.75
20	114O-57SSL-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.72	62.8	74.2	5337	0.257	0.81	0.71
21	114O-57SSLM-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.76	62.8	74.2	5015	0.246	0.77	0.63
22	114O-57SSLM-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.74	62.8	74.2	4719	0.167	0.72	0.61
23	114O-57SST-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.68	62.8	74.2	5936	0.504	0.91	0.83
24	114O-57SST-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.75	62.8	74.2	5930	0.422	0.91	0.76
25	114O-57SSTM-1/2-1-D-1.5-T1	0.1217	0.0588	A307	0.5	8.50	0.75	62.8	74.2	4639	0.262	0.71	0.59
26	114O-57SSTM-1/2-1-D-1.5-T2	0.1217	0.0588	A307	0.5	8.50	0.75	62.8	74.2	4744	0.239	0.72	0.60

Table A-21 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, e/d =1.5, Failure in Inside Sheet

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1	43O-30SSL-3/8-1-D-1.5-T1	0.0437	0.0294	A307	0.375	12.76	0.56	66.0	79.6	1458	0.280	0.75	0.62
2	43O-30SSL-3/8-1-D-1.5-T2	0.0437	0.0294	A307	0.375	12.76	0.56	66.0	79.6	1432	0.299	0.73	0.61
3	57O-43SSL-1/2-1-D-1.5-T2	0.0588	0.0437	A307	0.5	11.44	0.69	62.8	74.2	3321	0.339	1.01	0.92
4	57O-43SSL-1/2-1-D-1.5-T3	0.0588	0.0437	A307	0.5	11.44	0.75	62.8	74.2	3096	0.180	0.95	0.79
5	57O-43SSLM-1/2-1-D-1.5-T1	0.0588	0.0442	A307	0.5	11.31	0.75	62.8	74.2	3381	0.484	1.03	0.86
6	57O-43SSLM-1/2-1-D-1.5-T2	0.0588	0.0442	A307	0.5	11.31	0.74	62.8	74.2	2976	0.184	0.91	0.77
7	57O-43SST-1/2-1-D-1.5-T1	0.0588	0.0437	A307	0.5	11.44	0.76	62.8	74.2	3012	0.326	0.92	0.76
8	57O-43SST-1/2-1-D-1.5-T2	0.0588	0.0437	A307	0.5	11.44	0.75	62.8	74.2	2331	0.197	0.71	0.59
9	57O-43SST-1/2-1-D-1.5-T3	0.0588	0.0437	A307	0.5	11.44	0.73	62.8	74.2	2404	0.170	0.73	0.63
10	57O-43SSTM-1/2-1-D-1.5-T1	0.0588	0.0437	A307	0.5	11.44	0.74	62.8	74.2	2707	0.302	0.83	0.70
11	57O-43SSTM-1/2-1-D-1.5-T2	0.0588	0.0437	A307	0.5	11.44	0.74	62.8	74.2	3119	0.325	0.95	0.81
12	57O-57SSL-1/2-1-D-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.76	62.8	74.2	3040	0.351	0.93	0.76
13	57O-57SSL-1/2-1-D-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2606	0.177	0.80	0.66
14	57O-57SSL-1/2-1-D-1.5-T3	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2933	0.149	0.90	0.75
15	57O-57SSLM-1/2-1-D-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.76	62.8	74.2	3048	0.262	0.93	0.77
16	57O-57SSLM-1/2-1-D-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	3141	0.279	0.96	0.80
17	57O-57SST-1/2-1-D-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2928	0.295	0.89	0.75
18	57O-57SST-1/2-1-D-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.76	62.8	74.2	2901	0.265	0.89	0.73
19	57O-57SSTM-1/2-1-D-1.5-T1	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2788	0.283	0.85	0.71
20	57O-57SSTM-1/2-1-D-1.5-T2	0.0588	0.0588	A307	0.5	8.50	0.75	62.8	74.2	2740	0.232	0.84	0.70
21	73O-73SSL-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	3836	0.275	0.91	0.76
22	73O-73SSL-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4435	0.357	1.05	0.88
23	73O-73SSL-1/2-1-D-1.5-T3	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4008	0.441	0.95	0.79
24	73O-73SSLM-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	3798	0.492	0.90	0.75

Table A-21 Phase 2 Test Results for Double Shear Connections with Oversized and Slotted Holes, Single Bolt, *e/d* =1.5, Failure in Inside Sheet (continued)

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	d/t	e (in.)	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
25	73O-73SSLM-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4443	0.566	1.05	0.88
26	73O-73SSLM-1/2-1-D-1.5-T3	0.0760	0.0760	A307	0.5	6.58	0.75	63.6	74.1	4453	0.512	1.05	0.88
27	73O-73SST-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.76	63.6	74.1	4105	0.249	0.97	0.80
28	73O-73SST-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.74	63.6	74.1	3874	0.333	0.92	0.77
29	73O-73SSTM-1/2-1-D-1.5-T1	0.0760	0.0760	A307	0.5	6.58	0.72	63.6	74.1	4311	0.370	1.02	0.89
30	73O-73SSTM-1/2-1-D-1.5-T2	0.0760	0.0760	A307	0.5	6.58	0.73	63.6	74.1	4030	0.419	0.95	0.82
31	94O-57SST-1/2-1-D-1.5-T1	0.0971	0.0588	A307	0.5	8.50	0.73	75.3	87.3	5799	0.473	0.91	0.78
32	94O-57SST-1/2-1-D-1.5-T2	0.0971	0.0588	A307	0.5	8.50	0.71	75.3	87.3	5297	0.341	0.83	0.73
33	94O-94SSL-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	5868	0.364	0.92	0.77
34	94O-94SSL-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.73	75.3	87.3	5396	0.218	0.85	0.73
35	94O-94SSLM-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	6024	0.261	0.95	0.79
36	94O-94SSLM-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.75	75.3	87.3	6370	0.373	1.00	0.83
37	94O-94SST-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.73	75.3	87.3	5506	0.280	0.87	0.74
38	94O-94SST-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.72	75.3	87.3	5058	0.247	0.80	0.69
39	94O-94SSTM-1/2-1-D-1.5-T1	0.0971	0.0971	A307	0.5	5.15	0.76	75.3	87.3	6215	0.282	0.98	0.80
40	94O-94SSTM-1/2-1-D-1.5-T2	0.0971	0.0971	A307	0.5	5.15	0.71	75.3	87.3	5514	0.276	0.87	0.76
41	114O-114SSL-1/2-1-D-1.5-T1	0.1217	0.1217	A307	0.5	4.11	0.75	65.7	73.1	5132	0.255	0.77	0.64
42	114O-114SSL-1/2-1-D-1.5-T2	0.1217	0.1217	A307	0.5	4.11	0.75	65.7	73.1	5310	0.240	0.80	0.66
43	114O-114SSLM-1/2-1-D-1.5-	0.1217	0.1217	A307	0.5	4.11	0.76	65.7	73.1	7415	0.350	1.11	0.91
44	114O-114SSLM-1/2-1-D-1.5-	0.1217	0.1217	A307	0.5	4.11	0.75	65.7	73.1	6617	0.346	0.99	0.83
45	114O-114SST-1/2-1-D-1.5-T1	0.1217	0.1217	A307	0.5	4.11	0.75	65.7	73.1	7038	0.465	1.06	0.88
46	114O-114SST-1/2-1-D-1.5-T2	0.1217	0.1217	A307	0.5	4.11	0.76	65.7	73.1	6953	0.480	1.04	0.86
47	114O-114SSTM-1/2-1-D-1.5-	0.1217	0.1217	A307	0.5	4.11	0.72	65.7	73.1	6287	0.411	0.94	0.82
48	114O-114SSTM-1/2-1-D-1.5-	0.1217	0.1217	A307	0.5	4.11	0.70	65.7	73.1	7769	0.585	1.16	1.04

Table A-22 Phase 2 Test Results for Single Shear Connections with Rupture in Net Section, Single Bolt

No.	Specimen Label	SHT(1) t (in.)	SHT(2) t (in.)	Bolt Type	Bolt Dia. d (in.)	s (in.)	d/s	F_y (ksi)	F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS_US}	P_{test}/P_{NAS_CAN}
1*	73O-73S-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.48	0.20	63.6	74.1	4877	0.222	0.93	0.47
2*	73O-73S-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.47	0.20	63.6	74.1	5079	0.178	0.95	0.48
3*	73O-73O-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.49	0.20	63.6	74.1	4614	0.261	0.88	0.44
4*	73O-73O-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.51	0.20	63.6	74.1	4475	0.288	0.85	0.42
5*	73O-73SSL-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.49	0.20	63.6	74.1	4514	0.173	0.86	0.43
6*	73O-73SSL-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.51	0.20	63.6	74.1	4771	0.287	0.89	0.44
7*	73O-73SSLM-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.51	0.20	63.6	74.1	5157	0.348	0.98	0.49
8*	73O-73SSLM-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.52	0.20	63.6	74.1	4317	0.178	0.82	0.41
9*	73O-73SSLM-1/2-1-S-0.2-T3	0.0760	0.0760	Grade 8	0.5	2.49	0.20	63.6	74.1	4754	0.228	0.90	0.45
10*	73O-73SST-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.49	0.20	63.6	74.1	4628	0.336	0.88	0.44
11*	73O-73SST-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.51	0.20	63.6	74.1	4524	0.372	0.86	0.43
12*	73O-73SSTM-1/2-1-S-0.2-T1	0.0760	0.0760	Grade 8	0.5	2.52	0.20	63.6	74.1	4740	0.496	0.90	0.44
13*	73O-73SSTM-1/2-1-S-0.2-T2	0.0760	0.0760	Grade 8	0.5	2.51	0.20	63.6	74.1	4440	0.349	0.84	0.42
14	73O-73S-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.22	0.41	63.6	74.1	3413	0.205	0.94	0.96
15	73O-73S-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.23	0.41	63.6	74.1	3289	0.187	0.95	0.97
16	73O-73O-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.24	0.40	63.6	74.1	3314	0.158	0.95	0.96
17	73O-73O-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.20	0.42	63.6	74.1	3213	0.212	0.95	0.99
18	73O-73SSL-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.23	0.41	63.6	74.1	3515	0.158	1.01	1.03
19	73O-73SSL-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.28	0.39	63.6	74.1	3645	0.248	0.97	0.95
20	73O-73SSLM-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.25	0.40	63.6	74.1	3496	0.283	0.97	0.97
21	73O-73SSLM-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.26	0.40	63.6	74.1	3500	0.232	0.98	0.98
22	73O-73SST-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.21	0.41	63.6	74.1	2707	0.130	0.92	0.95
23	73O-73SST-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.21	0.41	63.6	74.1	2793	0.118	0.94	0.97
24	73O-73SSTM-1/2-1-S-0.4-T1	0.0760	0.0760	A307	0.5	1.23	0.41	63.6	74.1	2235	0.038	1.03	1.05
25	73O-73SSTM-1/2-1-S-0.4-T2	0.0760	0.0760	A307	0.5	1.21	0.41	63.6	74.1	2074	0.047	0.89	0.91

Note: * test performed in setup #2, the rest tests used setup #1.

American
Iron and Steel
Institute

1140 Connecticut Avenue, NW
Suite 705
Washington, DC 20036
www.steel.org

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