research report

Cold-Formed Steel Bolted Connections Without Washers on Oversized and Slotted Holes Phase 1

RESEARCH REPORT RP08-11

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Committee on Specifications
for the Design of Cold-Formed
Steel Structural Members

American Iron and Steel Institute

The material contained herein has been developed by researchers based on their research findings. The material has also been reviewed by the American Iron and Steel Institute Committee on Specifications for the Design of Cold-Formed Steel Structural Members. The Committee acknowledges and is grateful for the contributions of such researchers.

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Cold-Formed Steel Bolted Connections Without Washers on Oversized and Slotted Holes

Phase 1 Report

Submitted to

The American Iron and Steel Institute

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1 ABSTRACT

In cold-formed steel construction, bolted connections without washers for either oversized or short slotted holes may significantly expedite the building process and lower the cost. However, the current design specification does not include provisions for such connections, and washers are required to be installed for oversized holes or short slotted holes. The research presented in this report aims to experimentally investigate three typical failure modes in cold-formed steel bolted connections with the non-washer and oversized configurations. The three failure modes have been observed: sheet shear failure, sheet bearing failure, and fracture failure of the net section in the connected sheet. The research project consists of two phases. In Phase 1 the sheet shear and bearing failures will be studied, and in Phase 2 the fracture failure will be investigated. The test matrices include a full range of connection configurations covering various steel sheet thicknesses from 30 mil to 118 mil, different connection types of single and double shear using ASTM A307 and A325 bolt types, and high and low ductile steels.

2 INTRODUCTION

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

Preliminary experimental results show that failures, such as shear of the sheet, bearing or piling up of material in front of the bolt, and tearing of the sheet in the net section, usually occur in cold-formed steel bolted connections. Figure 2-1 illustrates these typical failure modes.

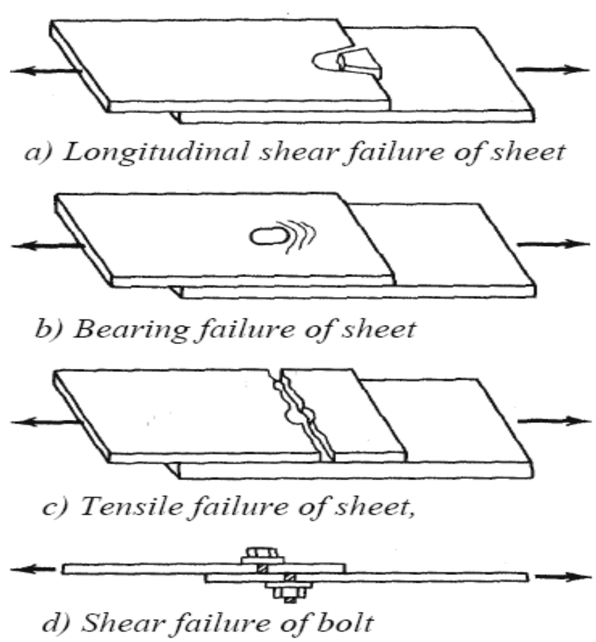


Fig 2-1 Typical Failures of Bolted Cold-Formed Steel Connections

3 BACKGROUND

The bolted connections in cold-formed steel may fail in four types of failure: Type I Shear of the sheet; Type II Bearing of the sheet, Type III Fracture in the net section of the sheet, Type IV Shear in the bolt, as shown in Figure 1.

The current North American Specification for the Design of Cold-Formed Steel Structural Members (NAS 2007) provides design provisions for those four types of failure respectively. NAS (2007) also stipulates the dimensions of the perforations, either holes or short slots, and the use of washers. The hole dimensions together with the use of washers may significantly influence the first three types of failure. The NAS (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.**”** This research project investigates the three failure modes of the cold-formed steel bolted connections without washers on oversized and short slotted holes.

The experimental study will be divided into two phases. In Phase 1, the shear and the bearing failures of the sheets will be investigated. In Phase 2, the fracture failure of the net section of the sheets will be studied. The suggested test matrices are designed to include a wide range of connection configurations including: (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; (4) the bolt type – ASTM 307 (2007) and ASTM 325 (2007); (5) the material ductility in sheets - low and high; (6) the diameter of the bolt – ¼”, ½”, $^{5}/_{8}$”.

Ultimately, the test results will be compared to the current NAS design provisions for connections with non-washer and standard holes. New design provisions will be developed to account for the configurations combining non-washers and oversized oversized/short slotted holes.

4 RESEARCH OBJECTIVES AND PLAN

The main research objectives are to experimentally investigate the behavior and strength of cold-formed steel bolted connections without washers when the steel sheets have oversized and short slotted holes and to develop appropriate design equations for such connections. Type I, II, and III failures of the specific bolted connections will be addressed in this study as described in Sections 3.1 and 3.2.

4.1 PHASE 1 RESEARCH OBJECTIVES

1. Study the shear failure, Type I failure, of cold-formed steel sheets in bolted connections without washers for oversized and short slotted holes and examine the applicability of the NAS Section E3.1 with the test results.
2. Study the bearing failure, Type II failure, of the connected sheets without considering the deformation of the hole, and examine the applicability of NAS Section E3.3.1 with the test results.
3. Study the bearing failure, Type II failure, of cold-formed steel sheets bolted connections without washers for oversized and short slotted holes considering the deformation of the hole, and examine the applicability of NAS Section E3.3.2 to bolted connections without washers on the oversized and short slotted holes.
4. Study the performance of the two grades of bolts, A307 and A325, throughout Type I and II failures.
5. Study the behavior of the low ductility and high ductility steel in the connections.

4.2 PHASE 2 RESEARCH OBJECTIVES

1. Study the fracture failure, Type III failure, for the bolted connections without washers for oversized and short slotted holes, and examine the applicability of NAS Section E3.2 (1) to the results.
2. Study the performance of the two grades of bolts, A307 and A325, in the Type III failures.
3. Study the behavior of the low ductility and high ductility steel in the Type III failures.

4.3 WORK PLAN AND DELIVERABLES

The two-year project consists of two phases. In Phase 1, sheet shear failure and bearing failure in the connected sheet (Types I and II failures) of bolted connections without washers on oversized and short slotted holes has been investigated and is reported in this progress report.. In Phase 2, the fracture in the net section of the connected sheet (Type III failure) for bolted connections using oversized and short slotted holes without wahers will be studied. The work plan is shown below:

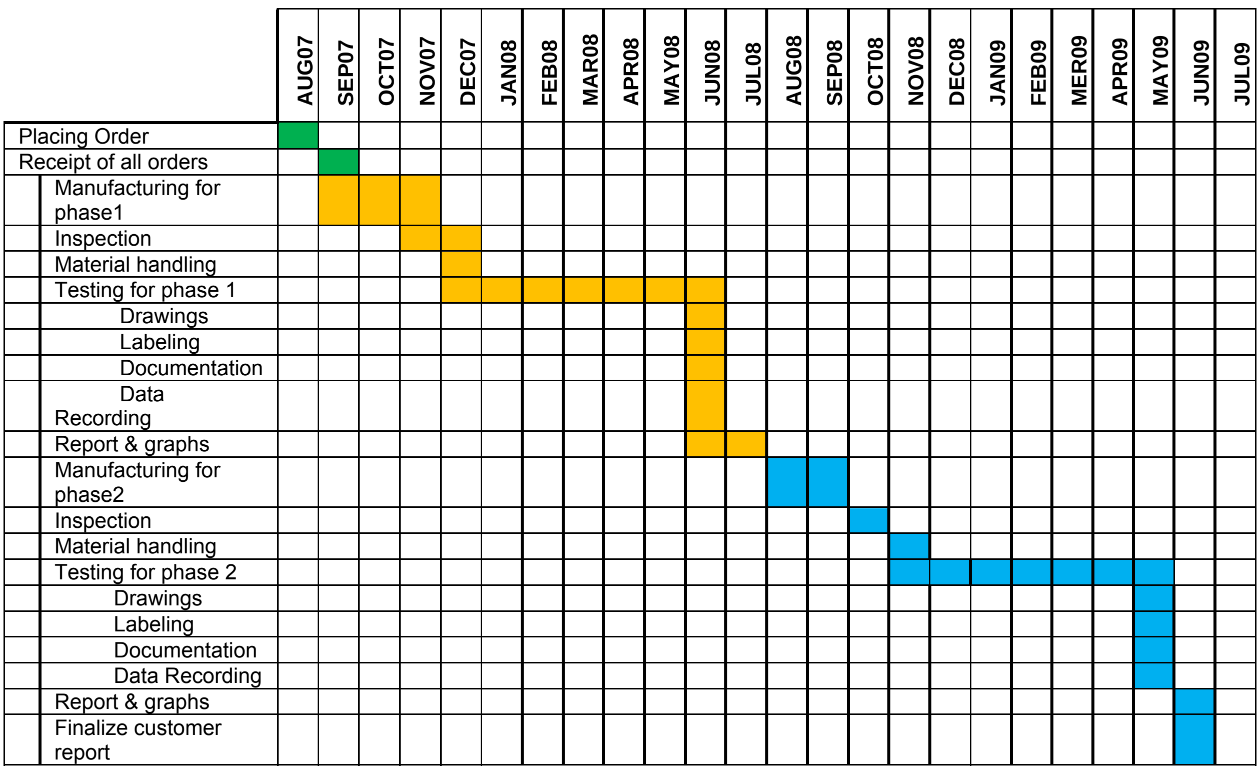


Fig 4-1 Preliminary Work Plan

The final project report will be submitted by the end of July 2009. Ballots written in specification-type language and the associated commentaries will be submitted to the AISI Committee on Specifications prior to the summer meetings in 2009.

5 LITERATURE REVIEW

5.1 SHEET SHEAR STRENGTH METHOD

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 and Schuster 2002). It was found that the shear strength of the sheet, Type I failure, depends on the thinnest sheet thickness (t), the tensile strength of connected sheet (F_u), and the distance from the center of hole to the nearest edge of adjacent hole or to the end of the connected sheet parallel to the direction of applied force (e). The nominal shear strength per bolt (P_n) can be expressed as Equation 5.1 (Eq. E3.1-1 in NAS 2007).

$$P_n = t\, e\, F_u \tag{5.1}$$

Where

P_n = nominal shear strength per bolt (lbs)

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

t = uncoated sheet thickness (inches)

F_u = tensile strength of sheet (psi)

It was also found that the 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. NAS (2007) Eq E3.1-1 implies that the influence of the presence of washers to the strength of Type I failure can be ignored in design.

5.2 BEARING STRENGTH METHOD

When the edge distance in the bolted connections is considerably large (e/d > 2.5), the bearing failure may occur. The previously conducted tests indicate that the bearing strength primarily depends on the tensile strength of sheet, the thickness of thinnest 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) (Yu 1982, Zadanfarrokh & Bryan 1992, LaBoube & Yu 1995, Wallace & Schuster 2001, 2002). The presence of washers has significant impact on the bearing strength. The current design method for bearing strength in NAS (2007) was based on the research done by Wallace, Schuster, and LaBoube (2001, 2002) in which the Waterloo method and current NAS method were developed.

The Waterloo method for cold-formed steel bolted connections without washers on standard holes is expressed in Equation 5.2. The coefficient, C, can be considered as the bearing factor, which is a function of the ratio of the bolt diameter to the plate thickness, d/t.

$$P_n = C\ d\ t\ F_u \qquad (5.2)$$

Where

P_n = nominal bearing strength per bolt (lbf)

C = bearing factor, value from Table 1

d = nominal bolt diameter (inches)

t = uncoated sheet thickness (inches)

F_u = tensile strength of sheet (psi)

Table 5-1 Bearing Factor C, for Bolted Connections without Washers (Waterloo Method)

Ratio of fastener diameter to member thickness, d/t	C
d/t < 10	2.25
10 ≤ d/t ≤ 16.5	22.5/(d/t)
d/t > 16.5	1.35

The current NAS method (NAS 2007) for bearing strength of bolted connections with standard holes is presented in Equation 5.3. Unlike the Waterloo method, the NAS method is uses a linear function for the bearing factor, C. Furthermore the NAS utilizes a modification factor to account for the use of washers and the connection type. 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.

$$P_n = m_f \, C \, d \, t \, F_u \qquad (5.3)$$

Where

P_n = nominal bearing strength per bolt (lbf)

m_f = modification factor (0.75 for single shear without washers, 1.33 for inside sheet of double shear)

C = bearing factor, value from Table 2

d = nominal bolt diameter (inches)

t = uncoated sheet thickness (inches)

F_u = tensile strength of sheet (psi)

Table 5-2 Bearing Factor C, for Bolted Connections (NAS, 2007)

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

6 TEST SETUP

6.1 TESTING EQUIPMENTS AND METHOD FOR CONNECTION TESTS

The tensile tests were conducted on a 20 kip Instron 4482 universal testing machine. The deformation of the bolted connection was measured by an extensometer with a gauge length of 0.9843 in. Figure 6-1 shows the test setup.

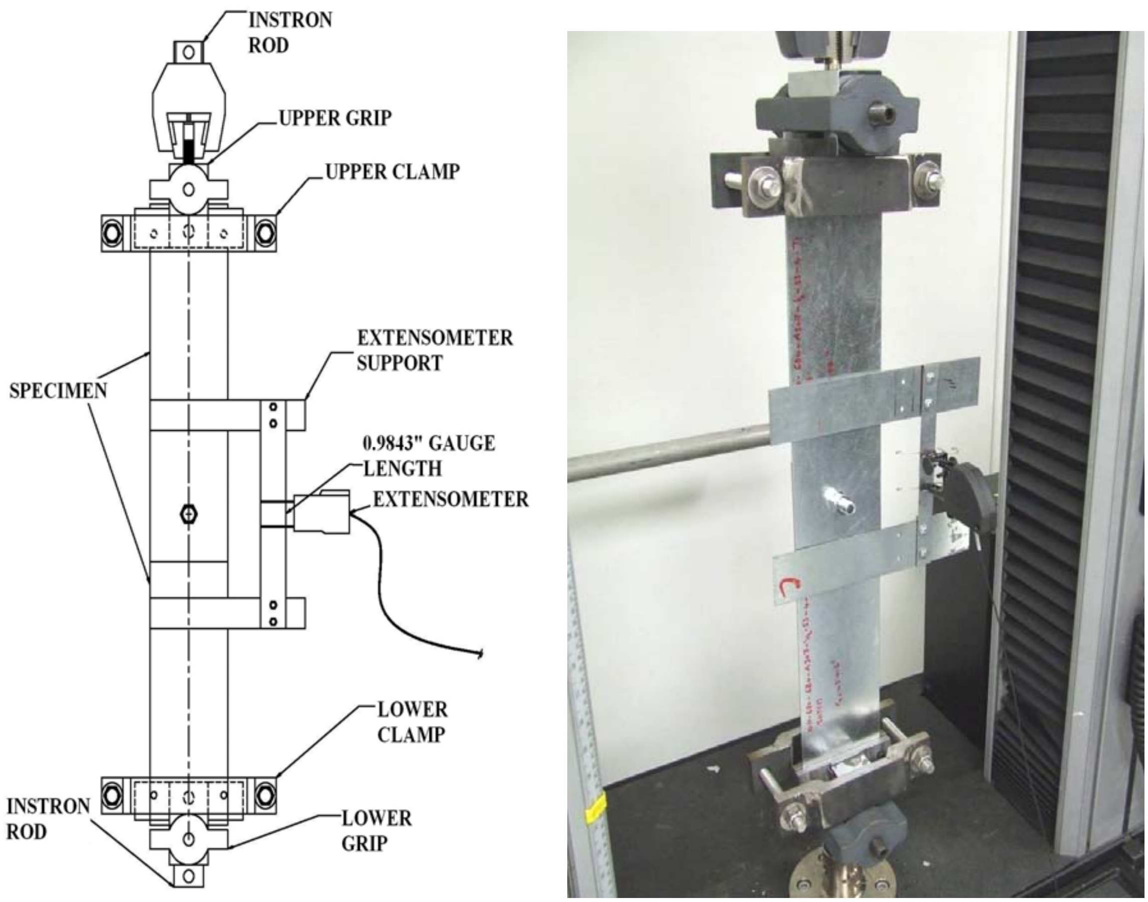


Fig 6-1 Setup for Tensile Tests on Bolted Connections

The tensile 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, moved upwards at a constant speed of 0.2 in./min. The applied force, the displacement of the top grip, and the deformation of the bolt were measured and recorded simultaneously by a PC during the test. All bolts were hand tightened and a torque wrench was used to ensure the applied torque did not exceed 40 lb-in.

Fig 6-2 Top and Bottom Grips

The two grips, the top and the bottom grips shown in Figure 6-2 were made specifically to hold the specimens. The new grips can handle up to 5 in. wide specimens. Additional clamps were designed and used to guarantee that specimens would not slip during the test by applying extra clamping force. When washers were used, the same procedure was followed. The washer dimensions are: 1.375 inches outer diameter, 0.57 inches inner diameter and 0.093 inches thickness. The A307 Bolt and A325 shank diameters are the same 0.493 inches. The head diameter for an A307 bolt is 0.739 inches and the head diameter for an A325 bolt is 0.862 inches. The LVDT instrument was assembled as shown in Figure 6-1 and the gauge length is 0.9843 inches.

6.2 COUPON TESTS FOR MATERIAL PROPERTIES

Coupon tests were also carried out by the Instron 4482 universal testing machine to obtain material properties of the connected sheets following ASTM E8 Specification (2007). Any coating on the cold-formed steel specimens was removed prior to the coupon tests. The tensile strain was measured by an Instron 2630-106 extensometer. The coupon tests were conducted in displacement control at a rate of 0.05 in./min and with a gauge length of 0.9843 inches. For each material thickness from the same coil, three coupons were cut and tested, and the average values were reported and used in the analysis.

7 TEST SPECIMENS

7.1 SPECIMEN CONFIGURATIONS

For both phases, the test matrix covers:

- Cold-formed steel sheet thicknesses ranged from 30 mil to 118 mil.
- Single shear and double shear connections with one bolt and two bolts.
- ASTM A307 Type A bolts (0.5 in. diameter, 1.25 in. long and 0.25 in. diameter, 1 in. long) and A325 bolts (0.5 in. diameter, 1.25 in. long) were used. Washers were not installed for the main test group.
- The dimensions of oversized holes and short slotted holes refer to the maximum sizes specified in Table E3a of NAS. Besides the NAS specified short-slotted hole, a MBMA slotted hole will also included in this research for 0.5 inch diameter bolts. The dimensions of oversized holes and short slots in this research are listed in Table 7-1.
- The oversized holes were all punched in the sheets. The short slotted holes were all fabricated by a CNC machine at the Simpson Strong Tie company.

Table 7-1 Dimensions of Oversize holes and Short Slots for Both Phases of Tests

Nominal bolt diameter, d (in.)	Oversized hole diameter, d_h (in.)	Short-slotted hole dimensions (in.)	MBMA short-slotted hole dimensions (in.)
< 1/2	d + 1/16	(d + 1/32) by (d + 1/4)	-
≥ 1/2	d + 1/8	(d + 1/16) by (d + 1/4)	(d + 1/16) by 7/8

- The research focused on the tensile strengths of 45 ksi and 65 ksi in the steel sheets. The choice of nominal tensile strength for each thickness of steel is subject to the product availability.

- High ductile steel was used for all the connection configurations. Low ductile steel were used for representative configurations.

The details of specimens for each phase are provided in the following sections.

Specimens of Phase 1 Tests

Sheet shear failure and bearing failure in the connected sheets (Type I and II failures) are the primary concerns in Phase 1 of the research. Therefore, the dimensions of specimens and test matrices were designed to ensure the occurrence of the desired failure mode.

Since Phase 1 tests focus on the shear failure and bearing failure in the connected sheet, the width of the specimens has to be sufficiently large to prevent net section fracture failure from occurring. Zadanfarrokh and Bryan (1992) recommended the width of the connected sheet w = 6.25 d for bearing tests with the nominal bolt diameter d ≥ 0.4 in. Figure 7-1 shows the dimensions recommended by Zadanfarrokh and Bryan (1992). Therefore the width of the sheets in the Phase 1 tests was set to 4 in.

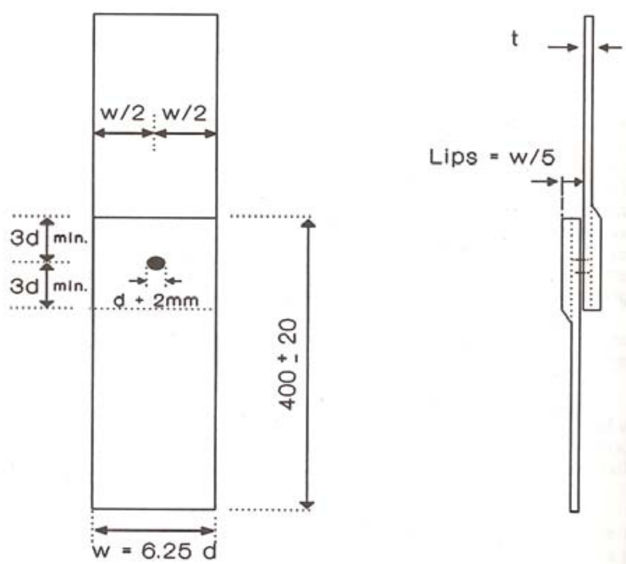


Fig 7-1 - Recommended test Dimensions for Structural Bolts (Zadanfarrokh and Bryan, 1992)

For the distance from the center of the bolt hole to the end of the connected sheet, e, it was found that a small ratio of e/d would lead to shear failure in the sheet. On the other hand, a sufficiently large e/d ratio would trigger bearing failure in the sheet. Research done by Chong and Matlock (1975), Gilchrist and Chong (1979), Yu (1982) indicated that e/d = 2.5 is approximately the transition point to distinguish between those two types of failures. Furthermore, the NAS (2007) requires a minimum e/d = 1.5 for cold-formed steel bolted connections. Therefore, e/d values in the proposed Phase 1 tests were chosen to be 4 for bearing failure and 1.5 for sheet shear failure. The length of each connected sheet, from edge to edge, was set to 15 in. which is based on the recommended value by Zadanfarrokh and Bryan (1992).

The sheet dimensions for the Phase 1 tests are shown in Figure 7-2 for one-bolt connections and in Figure 7-3 for two bolt connections. The distance between centers of bolt holes for the two-bolt connections equals to three times the nominal bolt diameter, d, which is based on the spacing requirement in Section E3.1 of the NAS (2007).

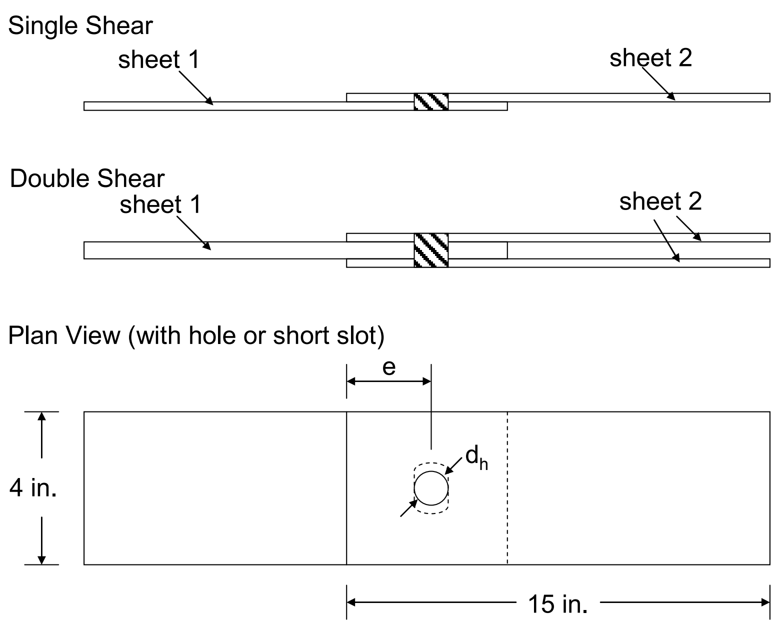


Fig 7-2 Dimensions of Specimens with One Bolt for Phase 1

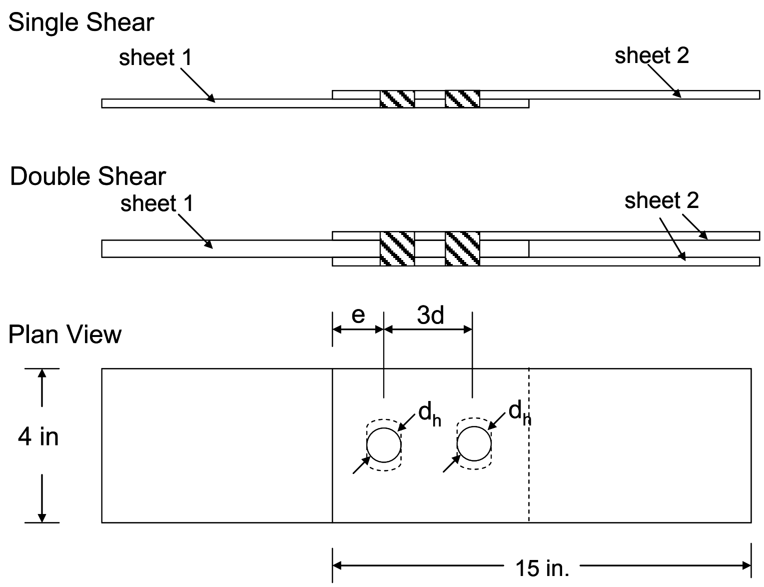


Fig 7-3 Dimensions of Specimens with Two Bolts for Phase 1

Specimens of Phase 2 Tests

The Phase 2 tests will study the facture in net section of connected sheets. The sheet dimensions need to be designed to avoid both shear failure and bearing failure in the sheet.

The edge distance, e, should be sufficiently large to prevent shear failure in the connected sheet. Zadanfarrokh and Bryan (1992) recommended the minimum e = 3d as shown in Figure 7-1. The proposed maximum diameter of the bolts is 0.625 in., therefore the distance from the center of bolt hole to the edge in the load direction is set to 3 in. for all the specimens in Phase 2. Further, in order to force the fracture in net section, the width of the specimen, s, has to be sufficiently small. Test results by Chong and Matlock (1975) indicated that when the dimensionless ratio d/s is less than 0.5, the fracture in nest section is likely to occur. Therefore, the ratios of d/s for the Phases 2 specimens are from 0.2 to 0.4. Figure 7-4 shows the sheet dimensions for one-bolt connections and Figure 7-5 shows the dimensions for two-bolt connections.

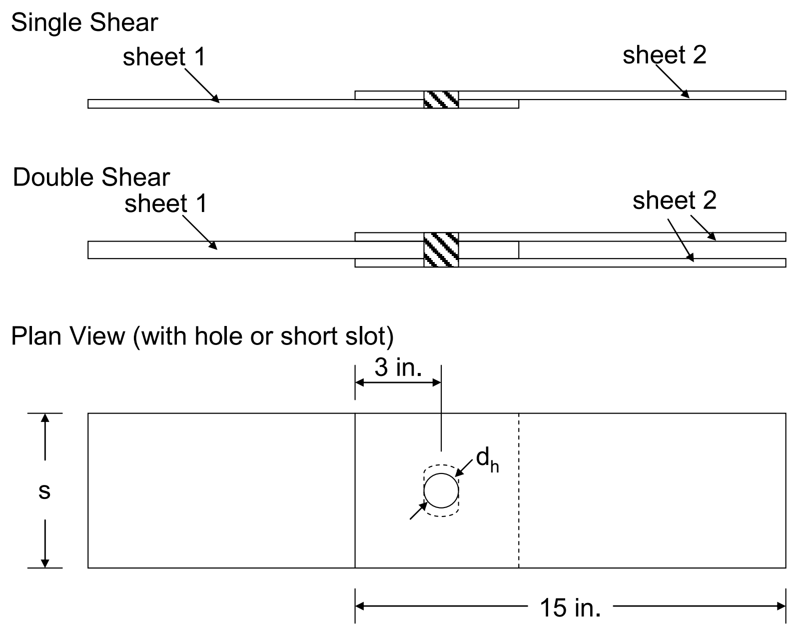


Fig 7-4 Dimensions of Specimens with One Bolt for Phase 2

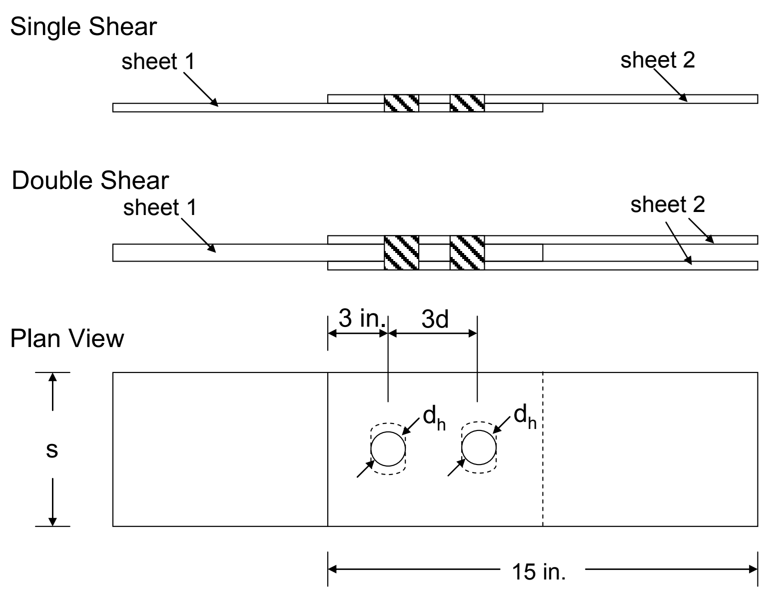
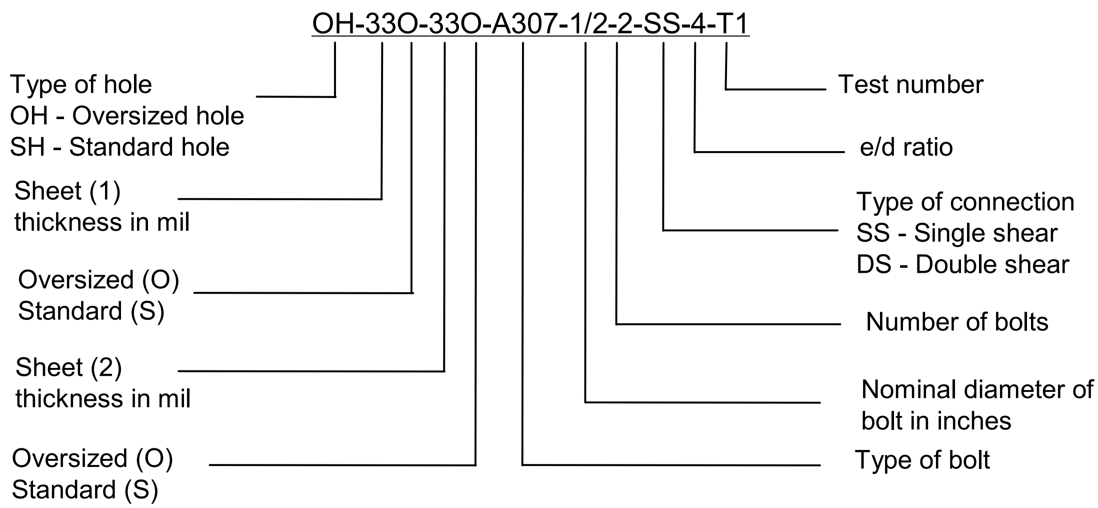


Fig 7-5 Dimensions of Specimens with Two Bolts for Phase 2

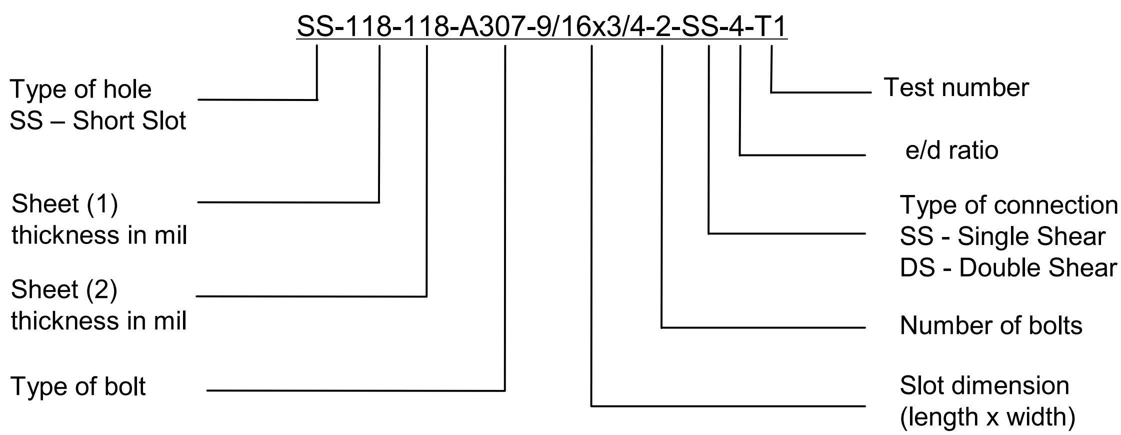
7.2 SPECIMEN LABELING

The specimens of Phase 1 were labeled as the following.

For tests with oversized holes:



For tests with short slots:



7.3 TEST MATRIX FOR PHASE 1 – BEARING AND SHEAR FAILURE OF THE SHEETS

The specimen configurations for the Phase 1 tests are listed in Tables 7-2 to 7-4. For each specimen configuration, two identical tests will be conducted. If the difference of the first two tests is greater than 10%, a third test will be performed.

Table 7-2 Test Matrix for Connections with Oversize Holes for Phase 1

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	Hole config.[3]	e/d	No. of Config.
1	118	118	H	A325	5/8	1	S	O/O	4	1
2	118	118	H	A325	1/2	1	S	O/O	1.5, 4	2
3	68	68	H	A307, A325	1/2	1	S	O/O	4	2
3	68	68	H	A307, A325	1/2	1	S	O/O	1.5	2
4	43	43	H	A307	1/4, 1/2	1	S	O/O	1.5, 4	4
5	33	33	H	A307	1/4, 1/2	1	S	O/O	1.5, 4	4
6	43	33	H	A307	1/2	1	S	O/O	4	1
7	118	68	H	A325	1/2	1	S	O/O	4	1
8	68	68	H	A325	1/2	1	S	O/S	1.5, 4	2
9	33	33	H	A307	1/2	1	S	O/S	1.5, 4	2
10	33	33	L	A307	1/2	1	S	O/O	1.5, 4	2
11	43	43	L	A307	1/2	1	S	O/O	1.5, 4	2
12	118	118	H	A325	5/8	1	D	O/O	4	1
13	118	118	H	A325	1/2	1	D	O/O	1.5, 4	2
14	68	68	H	A325	1/2	1	D	O/O	4	1
14	68	68	H	A325	1/2	1	D	O/O	1.5	1
15	43	43	H	A307	1/2	1	D	O/O	1.5, 4	2
16	33	33	H	A307	1/4, 1/2	1	D	O/O	1.5, 4	4
17	118	33	H	A307	1/2	1	D	O/O	4	1
18	118	43	H	A307	1/2	1	D	O/O	4	1
19	33	33	L	A307	1/2	1	D	O/O	1.5, 4	2
20	43	43	L	A307	1/2	1	D	O/O	1.5, 4	2
21	118	118	H	A325	1/2, 5/8	2	S	O/O	4	2
22	68	68	H	A325	1/2	2	S	O/O	1.5, 4	2
23	43	43	H	A307	1/2	2	S	O/O	1.5, 4	2
24	33	33	H	A307	1/2, 1/4	2	S	O/O	1.5, 4	4
25	43	33	H	A307	1/2	2	S	O/O	4	1
26	118	68	H	A325	1/2	2	S	O/O	4	1
27	33	33	L	A307	1/2	2	S	O/O	1.5, 4	2
28	43	43	L	A307	1/2	2	S	O/O	1.5, 4	2
29	118	118	H	A325	5/8	2	D	O/O	4	2
30	118	118	H	A325	1/2	2	D	O/O	1.5, 4	2
31	68	68	H	A325	1/2	2	D	O/O	1.5, 4	2
32	43	43	H	A307	1/2	2	D	O/O	1.5, 4	4
33	33	33	H	A307	1/4, 1/2	2	D	O/O	1.5, 4	2
34	118	33	H	A307	1/2	2	D	O/O	4	1
35	118	43	H	A307	1/2	2	D	O/O	4	1
36	33	33	L	A307	1/2	2	D	O/O	1.5, 4	2
37	43	43	L	A307	1/2	2	D	O/O	1.5, 4	2
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10\%$); L --- low-ductility steel ($F_u/F_y < 1.08$ or $\delta < 10\%$). 2: S --- single shear; D --- double shear. 3: O --- oversize hole; S --- standard hole.									Total	76 config. 152 tests

Table 7-3 Test Matrix for Connections with Short Slots (9/16" × 3/4") for Phase 1

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	e/d	No. of Config.
1	118	118	H	A307	1/2	1	S	1.5, 4	2
2	68	68	H	A307	1/2	1	S	1.5, 4	2
3	43	43	H	A307	1/2	1	S	1.5, 4	2
4	118	68	H	A307	1/2	1	S	4	1
5	118	118	H	A307	1/2	1	D	1.5, 4	2
6	68	68	H	A307	1/2	1	D	1.5, 4	2
7	118	118	H	A307	1/2	2	S	4	1
8	68	68	H	A307	1/2	2	S	1.5, 4	2
9	118	68	H	A307	1/2	2	S	4	1
10	118	118	H	A307	1/2	2	D	1.5, 4	2
11	68	68	H	A307	1/2	2	D	1.5, 4	2
Note: 1: H --- high-ductility steel (Fu/Fy≥1.08 or δ≥10%); L --- low-ductility steel (Fu/Fy<1.08 or δ<10%). 2: S --- single shear; D --- double shear.								Total	19 config.
									38 tests

Table 7-4 Test matrix for Connections with Short Slots (9/16" × 7/8") for Phase 1

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	e/d	No. of Config.
1	118	118	H	A307	1/2	1	S	1.5, 4	2
2	68	68	H	A307	1/2	1	S	1.5, 4	2
3	43	43	H	A307	1/2	1	S	1.5, 4	2
4	118	68	H	A307	1/2	1	S	4	1
5	118	118	H	A307	1/2	1	D	1.5, 4	2
6	68	68	H	A307	1/2	1	D	1.5, 4	2
7	118	118	H	A307	1/2	2	S	4	1
8	68	68	H	A307	1/2	2	S	1.5, 4	2
9	118	68	H	A307	1/2	2	S	4	1
10	118	118	H	A307	1/2	2	D	1.5, 4	2
11	68	68	H	A307	1/2	2	D	1.5, 4	2
Note: 1: H --- high-ductility steel (Fu/Fy≥1.08 or δ≥10%); L --- low-ductility steel (Fu/Fy<1.08 or δ<10%). 2: S --- single shear; D --- double shear.								Total	19 config.
									38 tests

7.4 TEST MATRIX FOR PHASE 2 – FRACTURE FAILURE OF THE SHEETS

Tables 7-5 through 7-7 summarize the specimen configurations in Phase 2 tests. For each specimen configuration, two identical tests will be conducted. If the difference of the first two tests is greater than 10%, a third test will be performed.

Table 7-5 Test Matrix for Connections with Short Slots (9/16" × 3/4") for Phase 2

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	d/s	No. of Config.
1	118	118	H	A325	1/2	1	S	0.25, 0.33	2
2	68	68	H	A307, A325	1/2	1	S	0.25, 0.33	4
5	118	68	H	A325	1/2	1	S	0.25, 0.33	2
7	68	68	H	A325	1/2	1	S	0.25, 0.33	2
11	118	118	H	A325	1/2	1	D	0.25, 0.33	2
12	68	68	H	A325	1/2	1	D	0.25, 0.33	2
19	118	118	H	A325	1/2	2	S	0.25, 0.33	2
20	68	68	H	A325	1/2	2	S	0.25, 0.33	2
23	118	68	H	A325	1/2	2	S	0.25, 0.33	2
27	118	118	H	A325	1/2	2	D	0.25, 0.33	2
28	68	68	H	A325	1/2	2	D	0.25, 0.33	2
31	118	68	H	A307	1/2	2	D	0.2, 0.3	2
33	68	68	L	A307	1/2	2	D	0.2, 0.33	2
Note: 1: H --- high-ductility steel (Fu/Fy≥1.08 or δ≥10%); L --- low-ductility steel (Fu/Fy<1.08 or δ<10%). 2: S --- single shear; D --- double shear.								Total	28 config.
									58 tests

Table 7-6 Test Matrix for Connections with Oversized Holes for Phase 2

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	Hole Config[3].	d/s	No. of Config.
1	118	118	H	A325	1/2, 5/8	1	S	O/O	0.25, 0.4	2
2	68	68	H	A307, A325	1/2	1	S	O/O	0.25, 0.4	4
3	43	43	H	A307	1/2	1	S	O/O	0.2, 0.4	2
4	33	33	H	A307	1/4, 1/2	1	S	O/O	0.2, 0.4	4
5	118	68	H	A325	1/2	1	S	O/O	0.25, 0.4	2
6	43	33	H	A307	1/2	1	S	O/O	0.2,0.4	2
7	68	68	H	A325	1/2	1	S	O/S	0.25, 0.4	2
8	33	33	H	A307	1/2	1	S	O/S	0.2, 0.4	2
9	43	43	L	A307	1/2	1	S	O/O	0.2, 0.4	2
10	33	33	L	A307	1/2	1	S	O/O	0.2, 0.4	2
11	118	118	H	A325	1/2 5/8	1	D	O/O	0.25, 0.4	4
12	68	68	H	A325	1/2	1	D	O/O	0.25, 0.4	2
13	43	43	H	A307	1/2	1	D	O/O	0.2, 0.4	2
14	33	33	H	A307	1/4, 1/2	1	D	O/O	0.2, 0.4	4
15	118	43	H	A307	1/2	1	D	O/O	0.2, 0.4	2
16	118	33	H	A307	1/2	1	D	O/O	0.2, 0.4	2
17	43	43	L	A307	1/2	1	D	O/O	0.2, 0.4	2
18	33	33	L	A307	1/2	1	D	O/O	0.2, 0.4	2
19	118	118	H	A325	1/2, 5/8	2	S	O/O	0.25, 0.4	4
20	68	68	H	A325	1/2	2	S	O/O	0.25, 0.4	2
21	43	43	H	A307	1/2	2	S	O/O	0.2, 0.4	2
22	33	33	H	A307	1/4, 1/2	2	S	O/O	0.2, 0.4	4
23	118	68	H	A325	1/2	2	S	O/O	0.25, 0.4	2
24	43	33	H	A307	1/2	2	S	O/O	0.2,0.4	2
25	43	43	L	A307	1/2	2	S	O/O	0.2, 0.4	2
26	33	33	L	A307	1/2	2	S	O/O	0.2, 0.4	2
27	118	118	H	A325	1/2, 5/8	2	D	O/O	0.25, 0.4	4
28	68	68	H	A325	1/2	2	D	O/O	0.25, 0.4	2
29	43	68	H	A307	1/2	2	D	O/O	0.2, 0.4	2
30	33	33	H	A307	1/4, 1/2	2	D	O/O	0.2, 0.4	4
31	118	68	H	A307	1/2	2	D	O/O	0.2, 0.4	2
32	118	33	H	A307	1/2	2	D	O/O	0.2, 0.4	2
33	68	68	L	A307	1/2	2	D	O/O	0.2, 0.4	2
34	33	33	L	A307	1/2	2	D	O/O	0.2, 0.4	2
Note: 1: H --- high-ductility steel ($F_u/F_y \geq 1.08$ or $\delta \geq 10\%$); L --- low-ductility steel ($F_u/F_y < 1.08$ or $\delta < 10\%$). 2: S --- single shear; D --- double shear. 3: O --- oversize hole; S --- standard hole.									Total	84 config. / 168 tests

Table 7-7 Test Matrix for Connections with Short Slots (9/16” × 7/8”) for Phase 2

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	d/s	No. of Config.
1	118	118	H	A325	1/2	1	S	0.25, 0.3	2
2	68	68	H	A307, A325	1/2	1	S	0.25, 0.3	4
5	118	68	H	A325	1/2	1	S	0.25, 0.3	2
7	68	68	H	A325	1/2	1	S	0.25, 0.3	2
11	118	118	H	A325	1/2	1	D	0.25, 0.3	2
12	68	68	H	A325	1/2	1	D	0.25, 0.3	2
19	118	118	H	A325	1/2	2	S	0.25, 0.3	2
20	68	68	H	A325	1/2	2	S	0.25, 0.3	2
23	118	68	H	A325	1/2	2	S	0.25, 0.3	2
27	118	118	H	A325	1/2	2	D	0.25, 0.3	2
28	68	68	H	A325	1/2	2	D	0.25, 0.3	2
31	118	68	H	A307	1/2	2	D	0.2, 0.3	2
33	68	68	L	A307	1/2	2	D	0.2, 0.3	2
Note: 1: H --- high-ductility steel (Fu/Fy≥1.08 or δ≥10%); L --- low-ductility steel (Fu/Fy<1.08 or δ<10%). 2: S --- single shear; D --- double shear.								Total	28 config.
									58 tests

8 TEST RESULTS

8.1 COUPON TESTS FOR MATERIAL PROPERTIES

Table 8-1 gives the experimentally determined material properties of each steel sheet thickness. Three coupon tests were conducted on each sheet thickness. The yield stress, F_y, were determined by the 0.2% offset method. The average values are provided in Table 8-1. Figure 8-1 shows the stress vs. strain curve of some steel sheet thicknesses. It can be seen that the high ductile steels (33 mil, 43 mil, 68 mil, 118 mil) meet the minimum requirements for material ductility specified by NAS (2007). The current NAS requires that the ratio of 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 low ductile steels studied in this research (30 mil / 0.75 mm, 39 mil / 1.00 mm) do not meet NAS's minimum requirements. The low ductile steel have significantly higher yield and tensile strengths as compared to the high ductile steels, and the low ductile steels do not have the typical strain hardening behavior that was commonly observed for the high ductile steels on the coupon tensile tests.

The 68 mil materials for the oversized hole (OH) and short slot (SS) specimens were from two different sources therefore they had different material properties. The actual material properties were used in analyses of this research to calculate the strength design values and to develop new design method.

Table 8-1 Material Properties

Nominal Sheet Thickness	Measured Thickness (in.)	Actual F_y (nominal) (ksi)	Actual F_u (nominal) (ksi)	F_u/F_y	Elongation on 2-in. Gage Length	Ductility
33 mil	0.0361	44.6 (33)	54.1 (45)	1.21	30%	High
43 mil	0.0439	51.6 (50)	70.3 (65)	1.36	20%	High
68 mil (OH)	0.0691	50.0 (50)	69.7 (65)	1.39	25%	High
68 mil (SS)	0.0698	46.1 (33)	54.5(45)	1.18	25%	High
118 mil	0.1305	45.3 (33)	52.2 (45)	1.15	25%	High
39 mil (1.00 mm)	0.0390	90.0	90.7	1.01	4%	Low
30 mil (0.75 mm)	0.0293	86.0	87.2	1.01	7.5%	Low

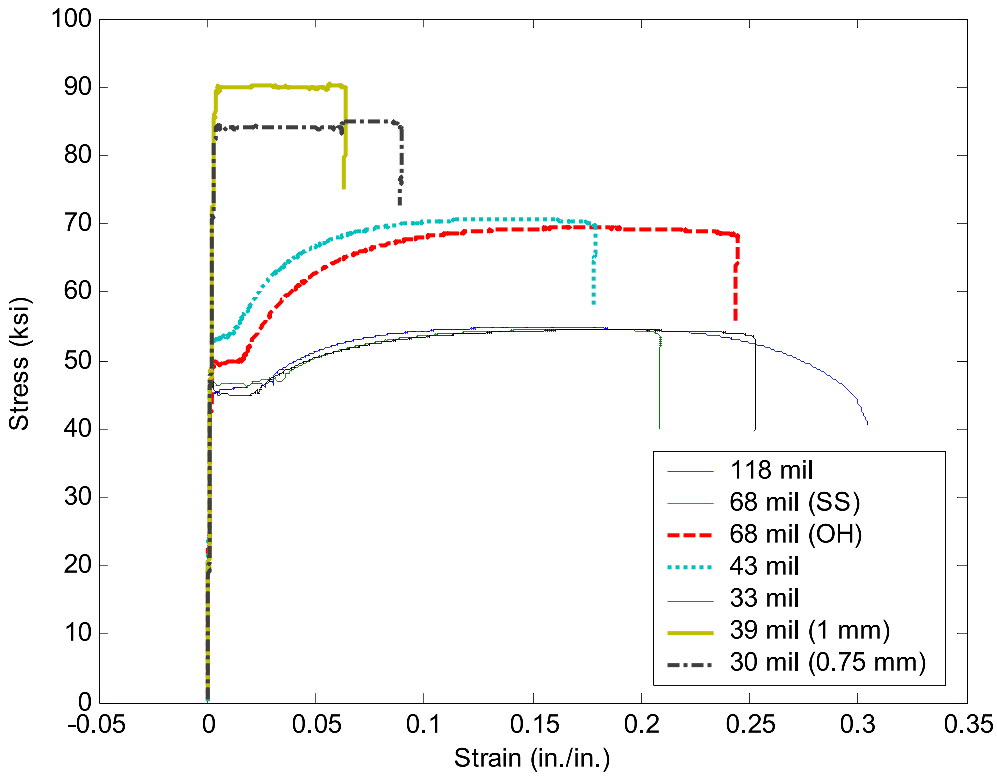


Fig 8-1 Stress – Strain Curves for Tested Materials

8.2 TENSILE TESTS ON BOLTED CONNECTIONS WITHOUT WASHERS ON OVERSIZED HOLES (MAIN GROUP)

8.2.1 Sheet Bearing Failure

The bearing failure of sheet (Type II) was investigated by tensile tests on connections with e/d ≥ 3. The test results are summarized in Tables 8-2, 8-3, 8-4, 8-5, where P_{test} is the tested peak load per bolt and "Δ" is the connection deformation at the peak load. Figures 8-2 and 8-3 respectively show the observed failure mode in the bearing strength tests on 43 mil single shear connections and double shear connections with one ½" A307 bolt. The bolt in the single shear connections was tilted to a large degree at failure, and the connected sheets curled outwards. For quite a few cases, the oversized hole was enlarged large enough during the tests to allow the bolt head to go through the hole, as shown in Figure 8-2. For the double shear connections, the bolt remained perpendicular to the loading direction during the test, and less curling deformation in the sheets was observed compared to the single shear connections.

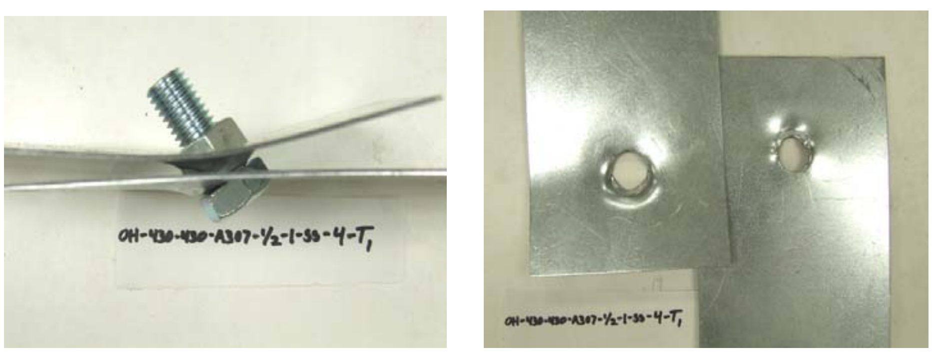


Fig 8-2 Sheet Bearing Failure of single shear connection OH-43O-43O-A307-1/2-1-SS-4-T1

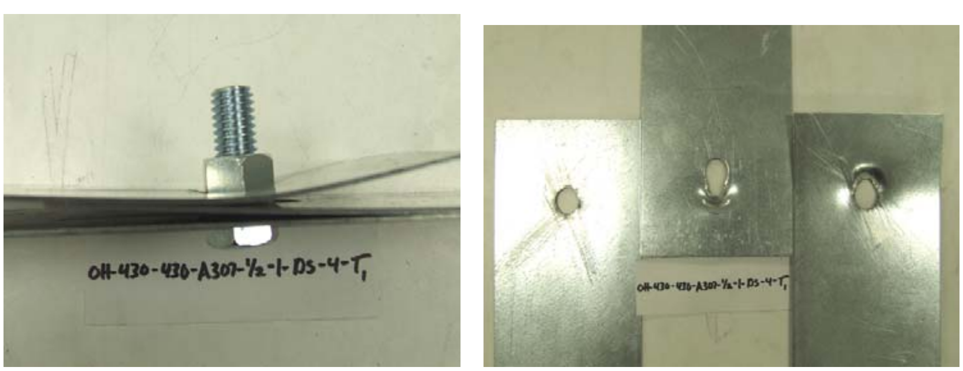


Fig 8-3 Sheet Bearing Failure of double shear connection OH-43O-43O-A307-1/2-1-DS-4-T1

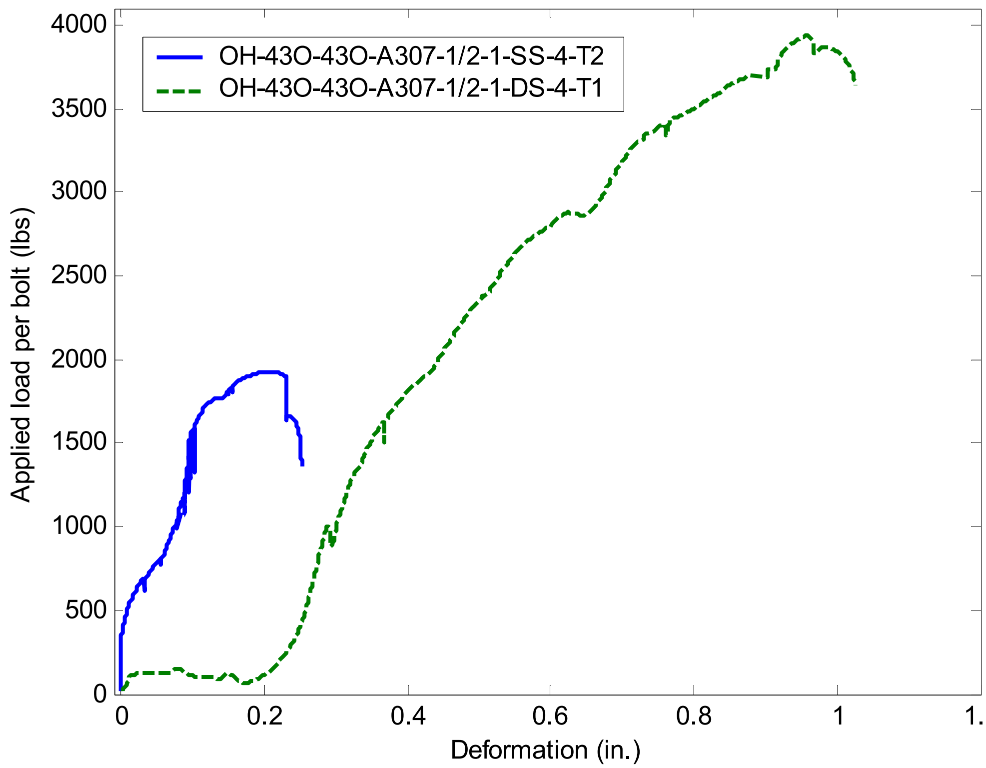


Fig 8-4 Load vs Deformation Curves for Bearing Strength Tests with One Bolt

Figure 8-4 presents a plot of the axial force vs. bolt deformation curves for two 43 mil connections with single ½" bolt. Because of the rotation of the bolt, the loading curve of single shear connection is not as gradual and smooth as that of the double shear connection, and the single shear connection yielded significantly lower strength than the double shear connection. The diameter of the oversized hole is 1/8 in. greater than the diameter of the ½" bolt therefore the connection can deform up to ¼ in. before the bolt and the sheet are engaged in load bearing. Therefore in the tests, it was found most of the connected sheets slipped for a certain distance before the load started increasing gradually. The two tests shown in Figure 8-4 demonstrated two extreme cases. The 43 mil single shear connection had immediate load increase after the test started because the bolt and the sheets were engaged before tests. However the 43 mil double shear connection deformed 0.2 in. before started bearing significant forces due to the gap between the sheets and the bolt. For connections using ½" bolt, the bolt slippage can vary between 0 to ¼ in. For connections using ¼" bolt, the slippage can vary from 0 to

1/8 in. And the magnitude of the bolt slippage depends on the initial position of the bolt related to the sheets. To avoid the influence by the initial bolt position, the connection deformations reported in this document are those measured from the point of bolt and sheets being engaged to the target.

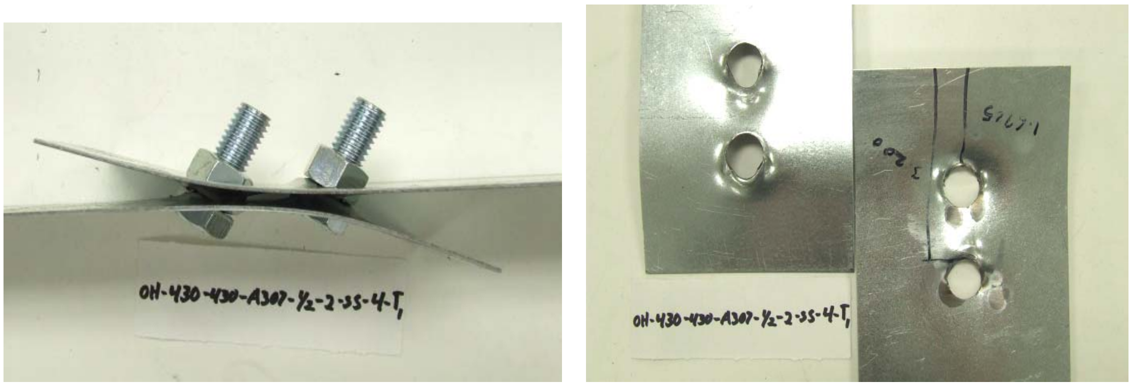


Fig 8-5 Sheet Bearing Failure of Single Shear Connection OH-43O-43O-A307-1/2-2-SS-4-T1

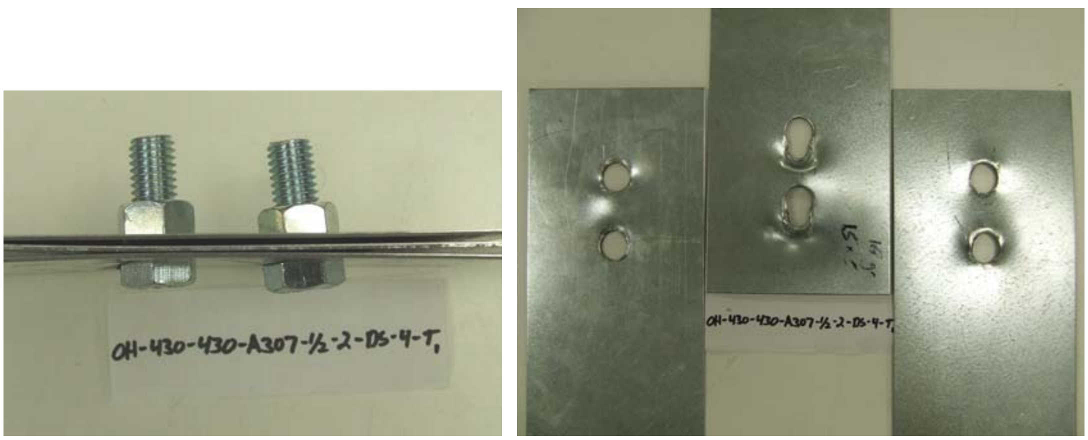


Fig 8-6 Sheet Bearing Failure of Double Shear Connection OH-43O-43O-A307-1/2-2-DS-4-T1

Figures 14 and 15 respectively show the failure mode of bearing strength tests on single shear and double shear connections with two bolts. The same failure mode as that of single bolt connections was observed in the two-bolt connections. Typical sheet bearing failure occurred on the single sheet of the double shear connections. In the tests on single shear connections, the bolt tilted and the sheet curled. The bolts titled in the single shear connections but remained straight in double shear connections. Figure 8-7 shows the load vs. deformation curves for two 43 mil connections with two ½" bolts, the single shear connection experienced 0.13 in. bolt slippage before the bolt and sheets were engaged. The 43 mil double shear connection shown in Figure 8-7 had no pre-test gap between the bolt and the sheets so that it could bear the load immediately after the connection started to deform.

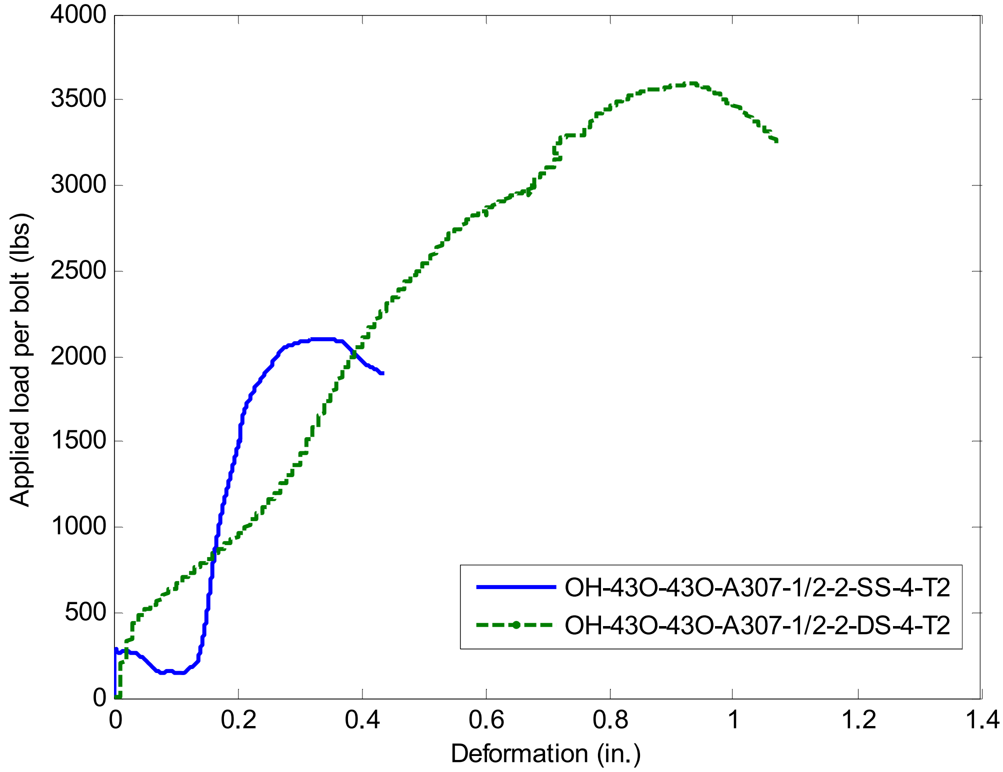


Fig 8-7 Load vs Deformation Curves for Bearing Strength Tests with Two Bolts

Table 8-2 Test Results for Single Shear Connections with Oversized Hole, Single Bolt, e/d >1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{NEW}
1	OH-118O-118O-A307-1/2-1-SS-4-T1	118	118	0.5	3.83	52.2	8499	0.360	1.11	1.16
2	OH-118O-118O-A307-1/2-1-SS-4-T2	118	118	0.5	3.83	52.2	8408	0.420	1.10	1.14
3	OH-68O-68O-A325-1/2-1-SS-4-T1	68	68	0.5	7.24	69.7	4685	0.682	0.86	0.92
4	OH-68O-68O-A325-1/2-1-SS-4-T2	68	68	0.5	7.24	69.7	4945	0.691	0.91	0.97
5	OH-68O-68O-A325-1/2-1-SS-4-T3	68	68	0.5	7.24	69.7	4649	0.382	0.86	0.91
6	OH-68O-68O-A307-1/2-1-SS-4-T1	68	68	0.5	7.24	69.7	3970	0.452	0.73	0.78
7	OH-68O-68O-A307-1/2-1-SS-4-T2	68	68	0.5	7.24	69.7	3925	0.547	0.72	0.77
8	OH-68O-68O-A307-1/2-1-SS-4-T3	68	68	0.5	7.24	69.7	4182	0.443	0.77	0.82
9	OH-43O-43O-A307-1/2-1-SS-4-T1	43	43	0.5	11.39	70.3	1904	0.206	0.58	0.77
10	OH-43O-43O-A307-1/2-1-SS-4-T2	43	43	0.5	11.39	70.3	1929	0.237	0.58	0.78
11	OH-43O-43O-A307-1/2-1-SS-4-T3	43	43	0.5	11.39	70.3	1885	0.200	0.57	0.76
12	OH-43O-43O-A307-1/4-1-SS-4-T1	43	43	0.25	5.69	70.3	1835	0.244	1.06	1.10
13	OH-43O-43O-A307-1/4-1-SS-4-T2	43	43	0.25	5.69	70.3	1894	0.275	1.09	1.14
14	OH-43O-43O-A307-1/4-1-SS-8-T1	43	43	0.25	5.69	70.3	1825	0.244	1.05	1.10
15	OH-43O-43O-A307-1/4-1-SS-8-T2	43	43	0.25	5.69	70.3	1725	0.276	0.99	1.04
16	OH-43O-43O-A307-1/4-1-SS-3-T1	43	43	0.25	5.69	70.3	1790	0.347	1.03	1.07
17	OH-43O-43O-A307-1/4-1-SS-3-T2	43	43	0.25	5.69	70.3	1823	0.319	1.05	1.09
18	OH-33O-33O-A307-1/2-1-SS-4-T1	33	33	0.5	13.85	54.1	1451	0.352	0.76	1.03
19	OH-33O-33O-A307-1/2-1-SS-4-T2	33	33	0.5	13.85	54.1	1444	0.566	0.75	1.02
20	OH-33O-33O-A307-1/4-1-SS-4-T1	33	33	0.25	6.93	54.1	1165	0.285	1.06	1.10
21	OH-33O-33O-A307-1/4-1-SS-4-T2	33	33	0.25	6.93	54.1	1213	0.281	1.10	1.15
22	OH-33O-33O-A307-1/4-1-SS-8-T1	33	33	0.25	6.93	54.1	1145	0.355	1.04	1.09
23	OH-33O-33O-A307-1/4-1-SS-8-T2	33	33	0.25	6.93	54.1	1232	0.397	1.12	1.17
24	OH-33O-33O-A307-1/4-1-SS-3-T1	33	33	0.25	6.93	54.1	1129	0.382	1.03	1.07
25	OH-33O-33O-A307-1/4-1-SS-3-T2	33	33	0.25	6.93	54.1	1136	0.321	1.03	1.08
26	OH-43O-33O-A307-1/2-1-SS-4-T1	43	33	0.5	13.85	54.1	1672	0.421	0.87	1.18
27	OH-43O-33O-A307-1/2-1-SS-4-T2	43	33	0.5	13.85	54.1	1635	0.424	0.85	1.16
28	OH-33O-33S-A307-1/2-1-SS-4-T1	33	33	0.5	13.85	54.1	1540	0.374	0.80	1.09
29	OH-33O-33S-A307-1/2-1-SS-4-T2	33	33	0.5	13.85	54.1	1548	0.304	0.81	1.09
30	OH-33O-33S-A307-1/2-1-SS-4-T2	33	33	0.5	13.85	54.1	1736	0.490	0.91	1.23
31	OH-30O-30O-A307-1/2-1-SS-4-T1	30	30	0.5	17.06	87.2	1620	0.319	0.74	0.97
32	OH-30O-30O-A307-1/2-1-SS-4-T2	30	30	0.5	17.06	87.2	1584	0.184	0.72	0.95
33	OH-39O-39O-A307-1/2-1-SS-4-T1	39	39	0.5	12.82	90.7	2423	0.373	0.67	0.91
34	OH-39O-39O-A307-1/2-1-SS-4-T2	39	39	0.5	12.82	90.7	2591	0.357	0.72	0.97

Table 8-3 Test Results for Single Shear Connections with Oversized Hole, Double Bolts, e/d >1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{NEW}
1	OH-43O-43O-A307-1/2-2-SS-4-T1	43	43	0.5	11.39	70.3	2101	0.333	0.63	0.85
2	OH-43O-43O-A307-1/2-2-SS-4-T2	43	43	0.5	11.39	70.3	2153	0.380	0.65	0.87
3	OH-33O-33O-A307-1/2-2-SS-4-T1	33	33	0.5	13.85	54.1	1306	0.400	0.68	0.92
4	OH-33O-33O-A307-1/2-2-SS-4-T2	33	33	0.5	13.85	54.1	1309	0.408	0.68	0.93
5	OH-33O-33O-A307-1/4-2-SS-4-T1	33	33	0.25	6.93	54.1	915	0.278	0.83	0.87
6	OH-33O-33O-A307-1/4-2-SS-4-T2	33	33	0.25	6.93	54.1	1106	0.263	1.01	1.05
7	OH-33O-33O-A307-1/4-2-SS-4-T3	33	33	0.25	6.93	54.1	1093	0.275	0.99	1.04
8	OH-33O-33O-A307-1/4-2-SS-8-T1	33	33	0.25	6.93	54.1	1149	0.329	1.05	1.09
9	OH-33O-33O-A307-1/4-2-SS-8-T2	33	33	0.25	6.93	54.1	1131	0.271	1.03	1.07
10	OH-33O-33O-A307-1/4-2-SS-3-T1	33	33	0.25	6.93	54.1	1170	0.381	1.06	1.11
11	OH-33O-33O-A307-1/4-2-SS-3-T2	33	33	0.25	6.93	54.1	1155	0.362	1.05	1.10
12	OH-43O-33O-A307-1/2-2-SS-4-T1	43	33	0.5	13.85	54.1	1752	0.311	0.91	1.24
13	OH-43O-33O-A307-1/2-2-SS-4-T2	43	33	0.5	13.85	54.1	1692	0.267	0.88	1.20
14	OH-30O-30O-A307-1/2-2-SS-4-T1	30	30	0.5	17.06	87.2	1701	0.303	0.77	1.02
15	OH-30O-30O-A307-1/2-2-SS-4-T2	30	30	0.5	17.06	87.2	1633	0.442	0.74	0.97
16	OH-39O-39O-A307-1/2-2-SS-4-T1	39	39	0.5	12.82	90.7	2232	0.255	0.62	0.84
17	OH-39O-39O-A307-1/2-2-SS-4-T2	39	39	0.5	12.82	90.7	2250	0.409	0.62	0.84

Table 8-4 Test Results for Double Shear Connections with Oversized Hole, Single Bolt, e/d >1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{NEW}
1	OH-68O-68O-A325-1/2-1-DS-4-T1	68	68	0.5	7.24	69.7	6824	0.664	0.71	0.86
2	OH-68O-68O-A325-1/2-1-DS-4-T2	68	68	0.5	7.24	69.7	6779	0.681	0.71	0.86
3	OH-43O-43O-A307-1/2-1-DS-4-T1	43	43	0.5	11.39	70.3	3933	0.471	0.67	1.02
4	OH-43O-43O-A307-1/2-1-DS-4-T2	43	43	0.5	11.39	70.3	3677	0.595	0.63	0.95
5	OH-33O-33O-A307-1/2-1-DS-4-T1	33	33	0.5	13.85	54.1	2637	0.606	0.78	1.20
6	OH-33O-33O-A307-1/2-1-DS-4-T2	33	33	0.5	13.85	54.1	2798	0.549	0.82	1.27
7	OH-33O-33O-A307-1/4-1-DS-4-T1	33	33	0.25	6.93	54.1	1888	0.345	0.97	1.15
8	OH-33O-33O-A307-1/4-1-DS-4-T2	33	33	0.25	6.93	54.1	1997	0.428	1.03	1.22
9	OH-33O-33O-A307-1/4-1-DS-8-T1	33	33	0.25	6.93	54.1	1912	0.396	0.98	1.17
10	OH-33O-33O-A307-1/4-1-DS-8-T2	33	33	0.25	6.93	54.1	1906	0.427	0.98	1.16
11	OH-33O-33O-A307-1/4-1-DS-3-T1	33	33	0.25	6.93	54.1	1768	0.409	0.91	1.08
12	OH-33O-33O-A307-1/4-1-DS-3-T2	33	33	0.25	6.93	54.1	1618	0.346	0.83	0.99
13	OH-30O-30O-A307-1/2-1-DS-4-T1	30	30	0.5	17.06	87.2	2380	0.401	0.61	0.91
14	OH-30O-30O-A307-1/2-1-DS-4-T2	30	30	0.5	17.06	87.2	2720	0.380	0.70	1.04
15	OH-30O-30O-A307-1/2-1-DS-4-T3	30	30	0.5	17.06	87.2	2548	0.466	0.65	0.98
16	OH-39O-39O-A307-1/2-1-DS-4-T1	39	39	0.5	12.82	90.7	3270	0.559	0.51	0.79
17	OH-39O-39O-A307-1/2-1-DS-4-T2	39	39	0.5	12.82	90.7	3335	0.675	0.52	0.80

Table 8-5 Test Results for Double Shear Connections with Oversized Hole, Double Bolts, *e/d* >1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}	P_{test}/P_{NEW}
1	OH-43O-43O-A307-1/2-2-DS-4-T1	43	43	0.5	11.39	70.3	3697	0.380	0.63	0.96
2	OH-43O-43O-A307-1/2-2-DS-4-T3	43	43	0.5	11.39	70.3	3595	0.351	0.61	0.93
3	OH-33O-33O-A307-1/2-2-DS-4-T1	33	33	0.5	13.85	54.1	2216	0.480	0.65	1.01
4	OH-33O-33O-A307-1/2-2-DS-4-T2	33	33	0.5	13.85	54.1	2004	0.464	0.59	0.91
5	OH-33O-33O-A307-1/4-2-DS-4-T1	33	33	0.25	6.93	54.1	1807	0.219	0.93	1.10
6	OH-33O-33O-A307-1/4-2-DS-4-T2	33	33	0.25	6.93	54.1	1994	0.343	1.02	1.22
7	OH-33O-33O-A307-1/4-2-DS-4-T3	33	33	0.25	6.93	54.1	1729	0.200	0.89	1.05
8	OH-33O-33O-A307-1/4-2-DS-4-T4	33	33	0.25	6.93	54.1	1675	0.366	0.86	1.02
9	OH-33O-33O-A307-1/4-2-DS-4-T5	33	33	0.25	6.93	54.1	1704	0.351	0.87	1.04
10	OH-33O-33O-A307-1/4-2-DS-8-T1	33	33	0.25	6.93	54.1	1740	0.587	0.89	1.06
11	OH-33O-33O-A307-1/4-2-DS-8-T2	33	33	0.25	6.93	54.1	1624	0.456	0.83	0.99
12	OH-33O-33O-A307-1/4-2-DS-3-T1	33	33	0.25	6.93	54.1	1594	0.474	0.82	0.97
13	OH-33O-33O-A307-1/4-2-DS-3-T2	33	33	0.25	6.93	54.1	1770	0.480	0.91	1.08
14	OH-33O-33O-A307-1/4-2-DS-3-T3	33	33	0.25	6.93	54.1	1536	0.197	0.79	0.94
15	OH-30O-30O-A307-1/2-2-DS-4-T1	30	30	0.5	17.06	87.2	2552	0.450	0.65	0.98
16	OH-30O-30O-A307-1/2-2-DS-4-T2	30	30	0.5	17.06	87.2	2681	0.287	0.69	1.03
17	OH-39O-39O-A307-1/2-2-DS-4-T1	39	39	0.5	12.82	90.7	3541	0.620	0.55	0.85
18	OH-39O-39O-A307-1/2-2-DS-4-T2	39	39	0.5	12.82	90.7	4014	0.600	0.63	0.97
19	OH-39O-39O-A307-1/2-2-DS-4-T3	39	39	0.5	12.82	90.7	3116	0.483	0.49	0.75
20	OH-39O-39O-A307-1/2-2-DS-4-T4	39	39	0.5	12.82	90.7	3422	0.515	0.54	0.83

8.2.2 Sheet Shear Failure

The shear failure of the sheet (Type I) was investigated by tensile tests on connections with e/d =1.5 and using one bolt. The test results are summarized in Tables 8-6 and 8-7, where P_{test} is the tested peak load per bolt and "Δ" is the connection deformation at the peak load. Figure 8-8 and 8-9 respectively show the typical failure mode observed in the shear strength tests on 33 mil single shear and double shear connections using one ½" A307 bolt. It was found that the bolt was titled significantly in the single shear tests due to the eccentric loading and the oversized hole dimension. As a result, the sheet warped and piled up at bearing area next to the hole. A combined failure mode of shear and bearing were achieved in the single shear tests, as shown in Figure 8-8. For the double shear tests, typical shear failure was observed on the inside sheet, the sheet fractured and deformed greatly at the hole edge. In the double shear tests the bolt remained perpendicular to the sheets. Figure 8-10 shows the load vs. deformation curves for 33 mil connection tests in sheet shear failure mode, both tests demonstrated bolt slippage of 0.1 in. Due to the tilting of the bolt, the single shear connection started losing stiffness at earlier stage than the double shear connection did and finally failed at lower load compared to that of the double shear connection.

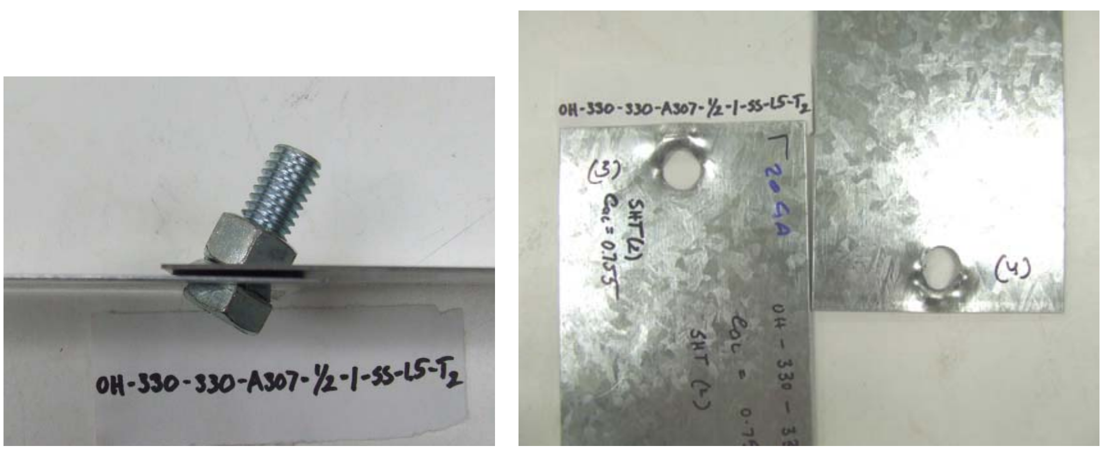


Fig 8-8 Sheet Shear Failure of Single Shear Connection OH-33O-33O-A307-1/2-1-SS-1.5-T2

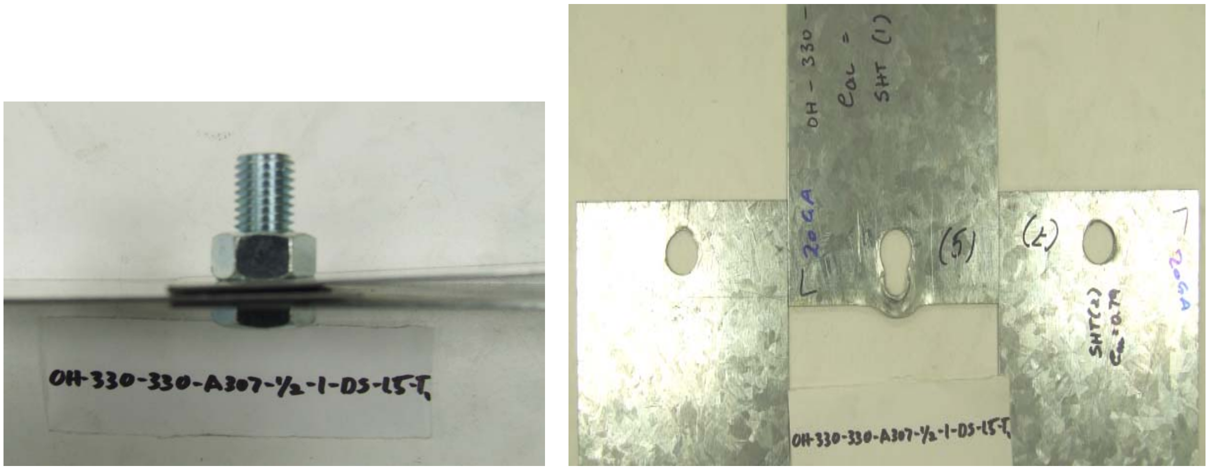


Fig 8-9 Sheet Shear Failure of Double Shear Connection OH-33O-33O-A307-1/2-1-DS-1.5-T1

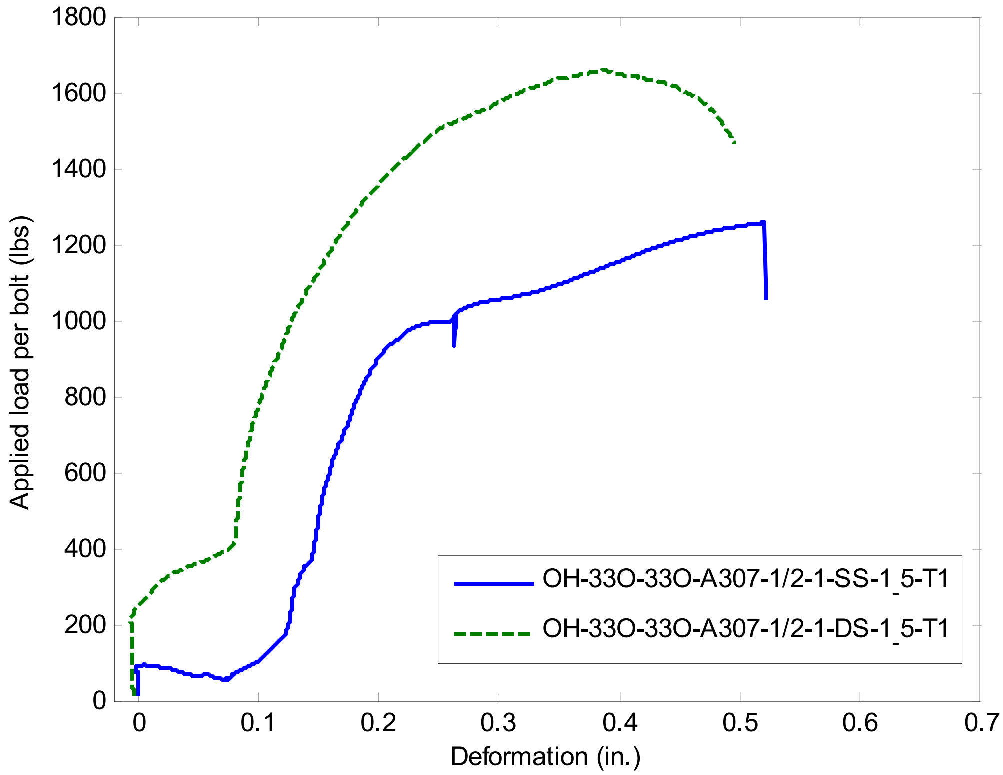


Fig 8-10 Load vs. Deformation Curves for Sheet Shear Strength Tests

Table 8-6 Test Results for Single Shear Connections with Oversized Hole, Single Bolt, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	OH-118O-118O-A307-1/2-1-SS-1.5-T1	118	118	0.5	3.83	0.750	52.2	5804	0.521	1.14
2	OH-118O-118O-A307-1/2-1-SS-1.5-T2	118	118	0.5	3.83	0.750	52.2	5885	0.588	1.15
3	OH-68O-68O-A325-1/2-1-SS-1.5-T1	68	68	0.5	7.24	0.750	69.7	3404	0.692	0.94
4	OH-68O-68O-A325-1/2-1-SS-1.5-T2	68	68	0.5	7.24	0.750	69.7	3363	0.680	0.93
5	OH-68O-68O-A307-1/2-1-SS-1.5-T1	68	68	0.5	7.24	0.750	69.7	3134	0.445	0.87
6	OH-68O-68O-A307-1/2-1-SS-1.5-T2	68	68	0.5	7.24	0.750	69.7	3112	0.410	0.86
7	OH-43O-43O-A307-1/2-1-SS-1.5-T1	43	43	0.5	11.39	0.750	70.3	2056	0.342	0.89
8	OH-43O-43O-A307-1/2-1-SS-1.5-T2	43	43	0.5	11.39	0.750	70.3	1951	0.171	0.84
9	OH-43O-43O-A307-1/4-1-SS-1.5-T1	43	43	0.25	5.69	0.375	70.3	1483	0.204	1.28
10	OH-43O-43O-A307-1/4-1-SS-1.5-T2	43	43	0.25	5.69	0.375	70.3	1482	0.118	1.28
11	OH-33O-33O-A307-1/2-1-SS-1.5-T1	33	33	0.5	13.85	0.750	54.1	1259	0.440	0.86
12	OH-33O-33O-A307-1/2-1-SS-1.5-T2	33	33	0.5	13.85	0.750	54.1	1303	0.400	0.89
13	OH-33O-33O-A307-1/4-1-SS-1.5-T1	33	33	0.25	6.93	0.375	54.1	985	0.253	1.34
14	OH-33O-33O-A307-1/4-1-SS-1.5-T2	33	33	0.25	6.93	0.375	54.1	1017	0.279	1.39
15	OH-33O-33S-A307-1/2-1-SS-1.5-T1	33	33	0.5	13.85	0.750	54.1	1723	0.483	1.18
16	OH-33O-33S-A307-1/2-1-SS-1.5-T2	33	33	0.5	13.85	0.750	54.1	1603	0.529	1.09
17	OH-30O-30O-A307-1/2-1-SS-1.5-T1	30	30	0.5	17.06	0.750	87.2	1727	0.197	0.90
18	OH-30O-30O-A307-1/2-1-SS-1.5-T2	30	30	0.5	17.06	0.750	87.2	1720	0.231	0.90
19	OH-39O-39O-A307-1/2-1-SS-1.5-T2	39	39	0.5	12.82	0.750	90.7	2645	0.435	1.00
20	OH-39O-39O-A307-1/2-1-SS-1.5-T3	39	39	0.5	12.82	0.750	90.7	2429	0.445	0.92

Table 8-7 Test Results for Double Shear Connections with Oversized Hole, Single Bolt, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	OH-43O-43O-A307-1/2-1-DS-1.5-T1	43	43	0.5	11.39	0.750	70.3	2266	0.218	0.98
2	OH-43O-43O-A307-1/2-1-DS-1.5-T2	43	43	0.5	11.39	0.750	70.3	1832	0.248	0.79
3	OH-43O-43O-A307-1/2-1-DS-1.5-T3	43	43	0.5	11.39	0.750	70.3	1789	0.239	0.77
4	OH-33O-33O-A307-1/2-1-DS-1.5-T1	33	33	0.5	13.85	0.750	54.1	1659	0.388	1.13
5	OH-33O-33O-A307-1/2-1-DS-1.5-T2	33	33	0.5	13.85	0.750	54.1	1637	0.447	1.12
6	OH-33O-33O-A307-1/4-1-DS-1.5-T1	33	33	0.25	6.93	0.375	54.1	1022	0.386	1.40
7	OH-33O-33O-A307-1/4-1-DS-1.5-T2	33	33	0.25	6.93	0.375	54.1	1017	0.341	1.39
8	OH-30O-30O-A307-1/2-1-DS-1.5-T1	30	30	0.5	17.06	0.750	87.2	1735	0.265	0.91
9	OH-30O-30O-A307-1/2-1-DS-1.5-T2	30	30	0.5	17.06	0.750	87.2	1810	0.325	0.94
10	OH-39O-39O-A307-1/2-1-DS-1.5-T1	39	39	0.5	12.82	0.750	90.7	2518	0.324	0.95
11	OH-39O-39O-A307-1/2-1-DS-1.5-T2	39	39	0.5	12.82	0.750	90.7	3046	0.559	1.15
12	OH-39O-39O-A307-1/2-1-DS-1.5-T3	39	39	0.5	12.82	0.750	90.7	2421	0.410	0.91

8.2.3 Sheet Bearing Failure and Sheet Shear Failure Combined

The main group of tests also included specific configurations with two bolts on one connection and those two bolts were expected to fail in two different failure modes. The specific configuration connections had the first hole punched close to the edge of the sheet (e/d = 1.5), and the second hole was placed 3 times of bolt diameter (3d) from the center of the first hole. Therefore the sheet shear failure was expected to occur at the first hole location and the sheet bearing failure was expected to happen at the second hole location. Figure 8-11 shows the typical failure mode on single shear connections, the two bolts were tilted greatly in the test and it caused the sheets to warp and pile up. The pure sheet shear failure was not observed on the first hole. Figure 8-12 shows the typical failure mode observed on double shear connections. The tilting of the two bolts was not significant, and the sheet bearing and sheet shear failures were observed on the second hole and the first hole respectively. Both Figure 8-11 and Figure 8-12 present 33 mil connections. The test results are summarized in Tables 8-8 and 8-9.

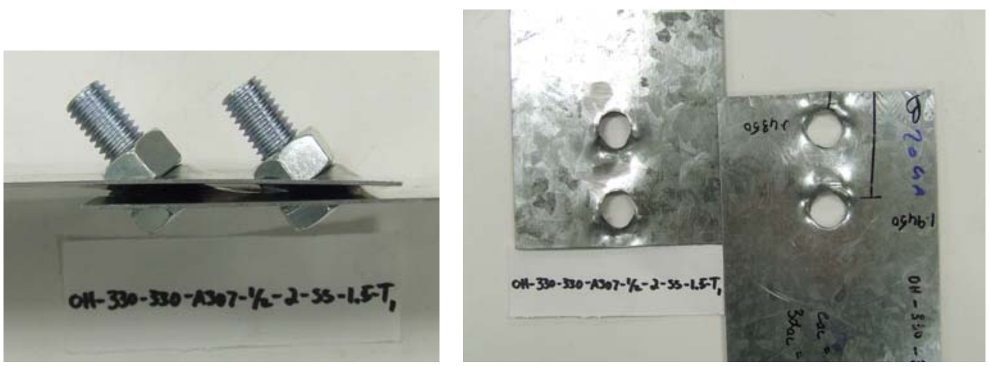


Fig 8-11 Failure Mode of Test OH-33O-33O-A307-1/2-2-SS-1.5-T1

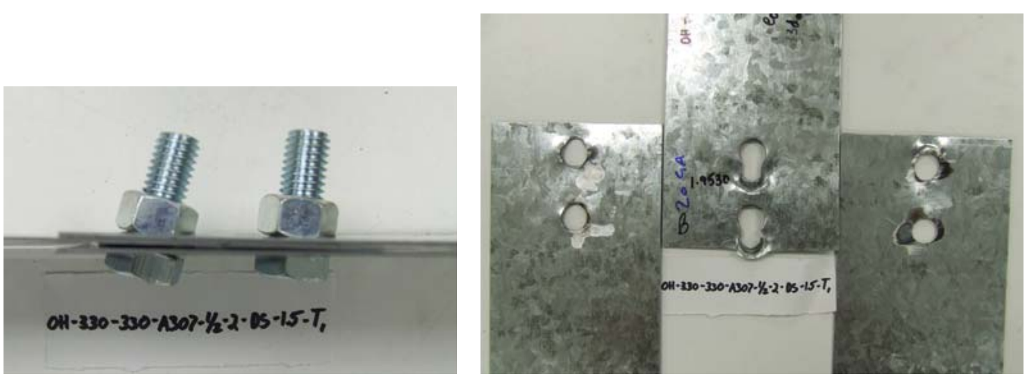


Fig 8-12 Failure Mode of Test OH-33O-33O-A307-1/2-2-DS-1.5-T1

Table 8-8 Test Results for Single Shear Connections with Oversized Hole, Double Bolts, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)
1	OH-43O-43O-A307-1/2-2-SS-1.5-T1	43	43	0.5	11.39	0.750	70.3	2005	0.309
2	OH-43O-43O-A307-1/2-2-SS-1.5-T2	43	43	0.5	11.39	0.750	70.3	2137	0.341
3	OH-33O-33O-A307-1/2-2-SS-1.5-T1	33	33	0.5	13.85	0.750	54.1	1333	0.352
4	OH-33O-33O-A307-1/2-2-SS-1.5-T2	33	33	0.5	13.85	0.750	54.1	1439	0.316
5	OH-33O-33O-A307-1/4-2-SS-1.5-T1	33	33	0.25	6.93	0.375	54.1	991	0.210
6	OH-33O-33O-A307-1/4-2-SS-1.5-T2	33	33	0.25	6.93	0.375	54.1	1069	0.243
7	OH-30O-30O-A307-1/2-2-SS-1.5-T1	30	30	0.5	17.06	0.750	87.2	1635	0.204
8	OH-30O-30O-A307-1/2-2-SS-1.5-T2	30	30	0.5	17.06	0.750	87.2	1891	0.436
9	OH-30O-30O-A307-1/2-2-SS-1.5-T3	30	30	0.5	17.06	0.750	87.2	1610	0.278
10	OH-39O-39O-A307-1/2-2-SS-1.5-T1	39	39	0.5	12.82	0.750	90.7	1841	0.245
11	OH-39O-39O-A307-1/2-2-SS-1.5-T2	39	39	0.5	12.82	0.750	90.7	1962	0.430

Table 8-9 Test Results for Double Shear Connections with Oversized Hole, Double Bolts, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)
1	OH-43O-43O-A307-1/2-2-DS-1.5-T1	43	43	0.5	11.39	0.750	70.3	2322	0.410
2	OH-43O-43O-A307-1/2-2-DS-1.5-T2	43	43	0.5	11.39	0.750	70.3	2623	0.563
3	OH-43O-43O-A307-1/2-2-DS-1.5-T3	43	43	0.5	11.39	0.750	70.3	2464	0.317
4	OH-33O-33O-A307-1/2-2-DS-1.5-T1	33	33	0.5	13.85	0.750	54.1	1784	0.439
5	OH-33O-33O-A307-1/2-2-DS-1.5-T2	33	33	0.5	13.85	0.750	54.1	1770	0.501
6	OH-33O-33O-A307-1/4-2-DS-1.5-T1	33	33	0.25	6.93	0.375	54.1	1200	0.309
7	OH-33O-33O-A307-1/4-2-DS-1.5-T2	33	33	0.25	6.93	0.375	54.1	1250	0.299
8	OH-30O-30O-A307-1/2-2-DS-1.5-T1	30	30	0.5	17.06	0.750	87.2	2051	0.416
9	OH-30O-30O-A307-1/2-2-DS-1.5-T2	30	30	0.5	17.06	0.750	87.2	1812	0.237
10	OH-30O-30O-A307-1/2-2-DS-1.5-T3	30	30	0.5	17.06	0.750	87.2	2144	0.317
11	OH-39O-39O-A307-1/2-2-DS-1.5-T1	39	39	0.5	12.82	0.750	90.7	2630	0.318
12	OH-39O-39O-A307-1/2-2-DS-1.5-T2	39	39	0.5	12.82	0.750	90.7	2494	0.295

8.3 TENSILE TESTS ON BOLTED CONNECTIONS WITHOUT WASHIERS ON OVERSIZED HOLES (ADDITIONAL GROUP)

In addition to the main test group, a series of additional tests on a small range of configurations were also performed. The purpose of the additional group of tests was to make direct comparison on the bearing strength between the connections with oversized holes and connections with standard holes, with or without washers. All the additional tests were on single shear connections with single A307 ½" bolt and e/d = 4. The following parameters are included in test configurations.

1. Oversized hole, with washers
2. Standard hole, with washers
3. Standard hole, without washers

The results of these additional tests are listed in Table 8-10. Figures 8-13 and 8-14 respectively shows the failure mode of the 43 mil connections with washers on standard hole and oversized hole. Compared to the connections without washers, the connections with washers demonstrated less tilting of the bolt and the larger hole deformation which resulted in higher bearing strength. Figure 8-15 shows the failure mode of a 43 mil connection without washer on standard hole. The bolt tilted but the nut and bolt head did not go through the hole and the hole was less deformed compared to tests with washers.

Table 8-10 Additional Tests on 33 mil and 43 mil Single Shear Connections

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Washer	Hole Config.	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	WW-OH-43O-43O-A307-1/2-1-SS-4-T1	43	43	Yes	Oversize	0.5	11.39	70.3	3710	0.601	0.84
2	WW-OH-43O-43O-A307-1/2-1-SS-4-T2	43	43	Yes	Oversize	0.5	11.39	70.3	3441	0.312	0.78
3	WW-SH-43S-43S-A307-1/2-1-SS-4-T1	43	43	Yes	Standard	0.5	11.39	70.3	3824	0.800	0.87
4	WW-SH-43S-43S-A307-1/2-1-SS-4-T2	43	43	Yes	Standard	0.5	11.39	70.3	3906	0.820	0.88
5	WW-SH-43S-43S-A307-1/2-1-SS-4-T3	43	43	Yes	Standard	0.5	11.39	70.3	3941	0.464	0.89
6	WW-SH-43S-43S-A307-1/2-1-SS-4-T4	43	43	Yes	Standard	0.5	11.39	70.3	4314	0.510	0.98
7	SH-43S-43S-A307-1/2-1-SS-4-T1	43	43	No	Standard	0.5	11.39	70.3	2437	0.441	0.74
8	SH-43S-43S-A307-1/2-1-SS-4-T2	43	43	No	Standard	0.5	11.39	70.3	2300	0.283	0.69
9	SH-43S-43S-A307-1/2-1-SS-4-T3	43	43	No	Standard	0.5	11.39	70.3	2385	0.231	0.72
10	WW-OH-33O-33O-A307-1/2-1-SS-4-T1	33	33	Yes	Oversize	0.5	13.85	54.1	2235	0.317	0.88
11	WW-OH-33O-33O-A307-1/2-1-SS-4-T2	33	33	Yes	Oversize	0.5	13.85	54.1	2323	0.438	0.91
12	WW-SH-33S-33S-A307-1/2-1-SS-4-T1	33	33	Yes	Standard	0.5	13.85	54.1	2864	0.327	1.12
13	WW-SH-33S-33S-A307-1/2-1-SS-4-T2	33	33	Yes	Standard	0.5	13.85	54.1	2754	0.426	1.08
14	WW-SH-33S-33S-A307-1/2-1-SS-4-T3	33	33	Yes	Standard	0.5	13.85	54.1	2574	0.642	1.01
15	WW-SH-33S-33S-A307-1/2-1-SS-4-T4	33	33	Yes	Standard	0.5	13.85	54.1	2686	0.540	1.05
16	SH-33S-33S-A307-1/2-1-SS-4-T1	33	33	No	Standard	0.5	13.85	54.1	1546	0.310	0.81
17	SH-33S-33S-A307-1/2-1-SS-4-T2	33	33	No	Standard	0.5	13.85	54.1	1547	0.501	0.81
18	SH-33S-33S-A307-1/2-1-SS-4-T3	33	33	No	Standard	0.5	13.85	54.1	1625	0.282	0.85
19	SH-33S-33S-A307-1/2-1-SS-4-T4	33	33	No	Standard	0.5	13.85	54.1	1546	0.337	0.81

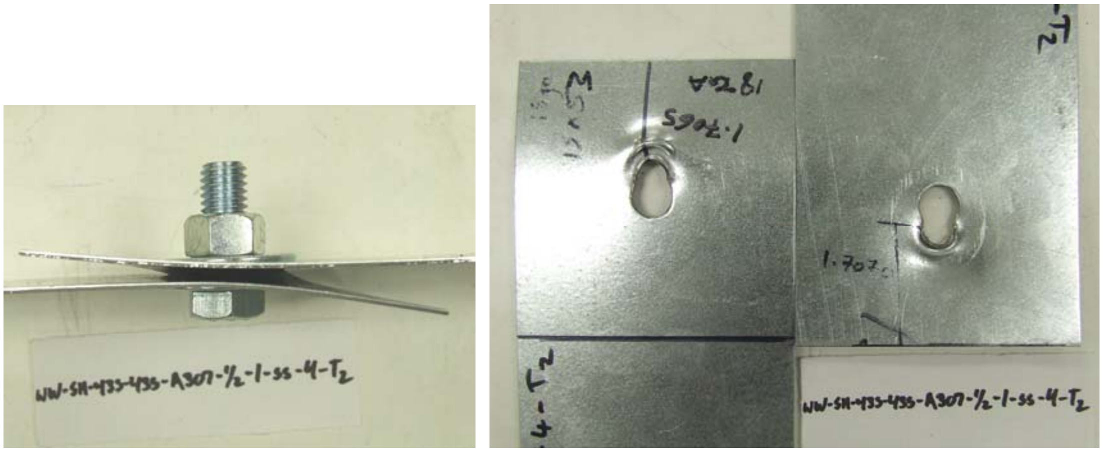


Fig 8-13 Failure Mode of Test WW-SH-43S-43S-A307-1/2-1-SS-4-T2

Fig 8-14 Failure Mode of Test WW-OH-43O-43O-A307-1/2-1-SS-4-T1

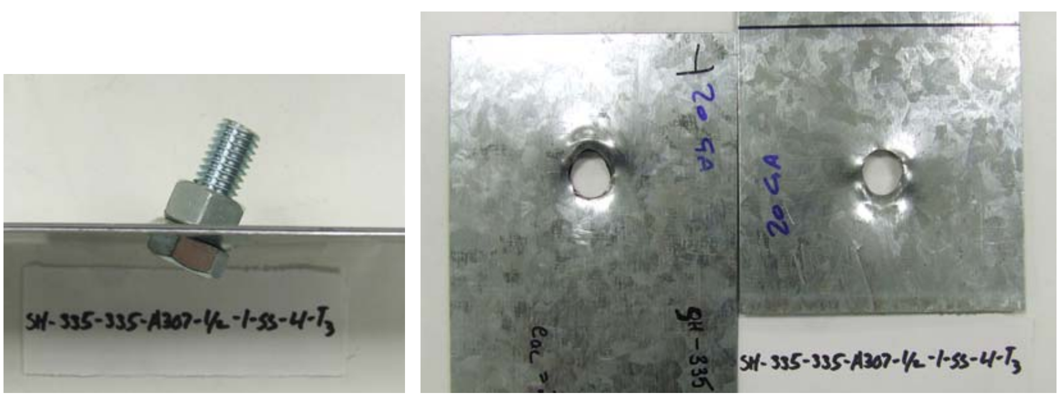


Fig 8-15 Failure Mode of Test SH-33S-33S-A307-1/2-1-SS-4-T3

8.4 TENSILE TESTS ON BOLTED CONNECTIONS WITHOUT WASHIERS ON SHORT SLOTTED HOLES

The strength and behavior of bolted connections without washers on short slotted holes was studied through series of tensile tests on 68 mil and 118 mil specimens using ½" diameter A307 Type A bolts. Two sizes of slotted holes were investigated: 9/16" by 3/4" and 9/16" by 7/8": The Phase 1 research focused on bearing failure and sheet shear failure mode.

8.4.1 Sheet Bearing Failure

The bearing failure was investigated on tensile tests on connections with e/d = 4. The results are summarized in Tables 8-11 and 8-12 for single shear and Tables 8-13 and 8-14 for double shear. Figure 8-16 illustrates a comparison of the load vs. deformation curves among the single shear connections with one bolt in bearing. Figures 8-17 through 8-20 show the failure mode of 68 mil and 118 mil single shear connections using single bolt. It was observed that the bolt tilted greatly in the single shear specimens and the bolt head and nut passed through the slotted hole causing the failure of the connections. The tilting of bolt was more significant in the connections with larger size slot therefore the connections with 9/16"×7/8" slots yielded lower bearing strength than the connections with 9/16"×3/4".

Similar results were also found on the single shear tests with two ½" diameter A207 bolts. Figures 8-21 and 8-22 show the bearing failure mode of the connections using 2 bolts with 9/16"×3/4" and 9/16"×7/8" slotted holes respectively. The bolts tilted greatly in both tests. The bolt heads and nuts went through the 9/16"×7/8" slots and caused separation of two sheets, shown in Figure 8-22. The two-bolt connections with smaller slot size (9/16"×3/4") systemically gave higher bearing strength than the connections with larger slot size (9/16"×7/8").

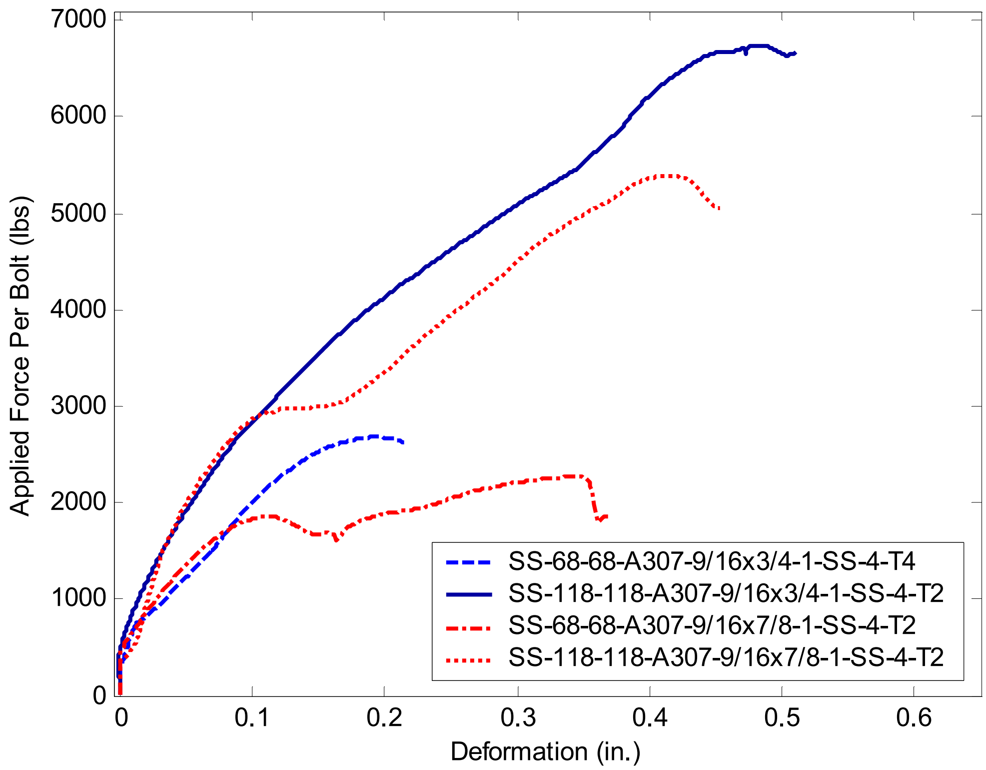


Fig 8-16 Load vs. Deformation Curves for Single Shear Connections with Single Bolt, Slotted Holes in Bearing,

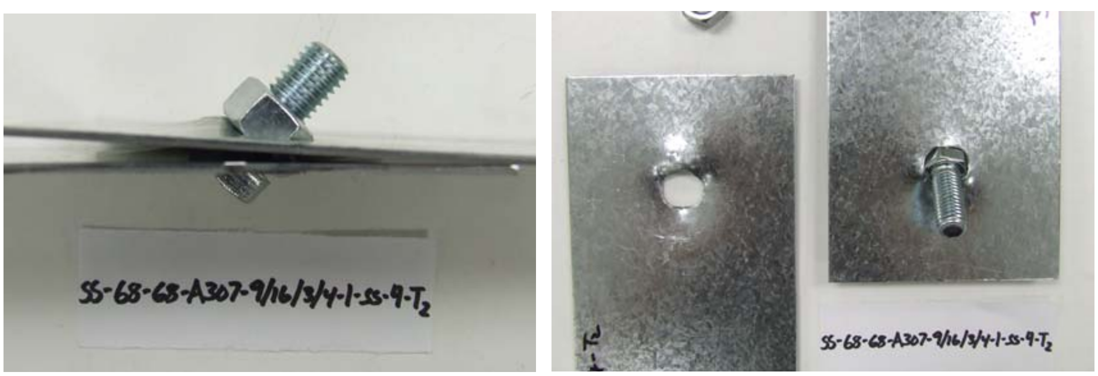


Fig 8-17 Failure Mode of Test SS-68-68-A307-9/16x3/4-1-SS-4-T2

Fig 8-18 Failure Mode of Test SS-68-68-A307-9/16x7/8-1-SS-4-T2

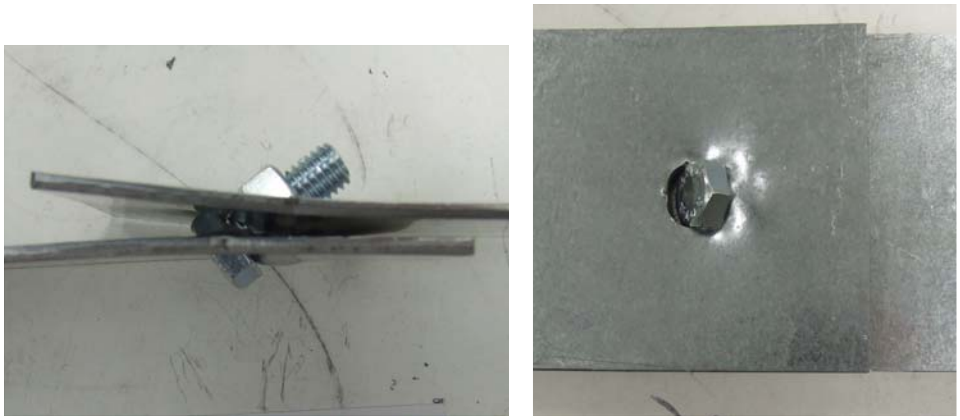


Fig 8-19 Failure Mode of Test SS-118-118-A307-9/16x3/4-1-SS-4-T2

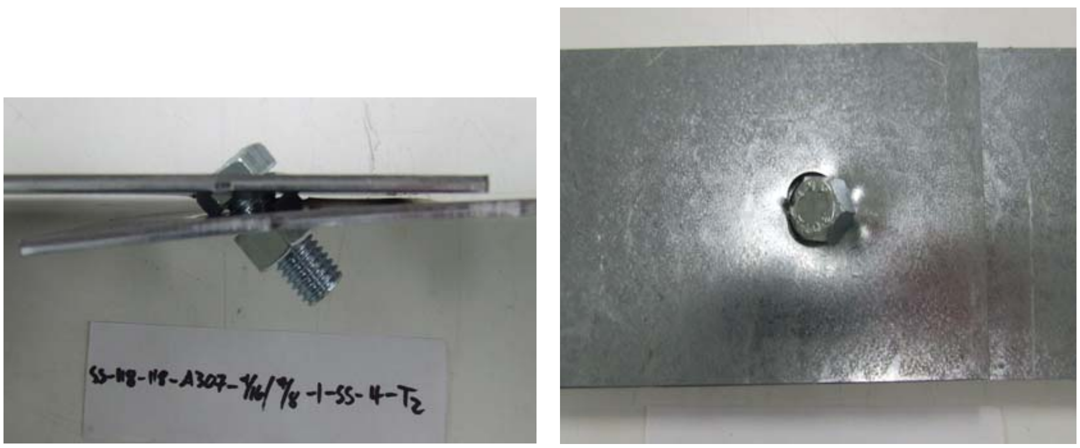


Fig 8-20 Failure Mode of Test SS-118-118-A307-9/16x7/8-1-SS-4-T2

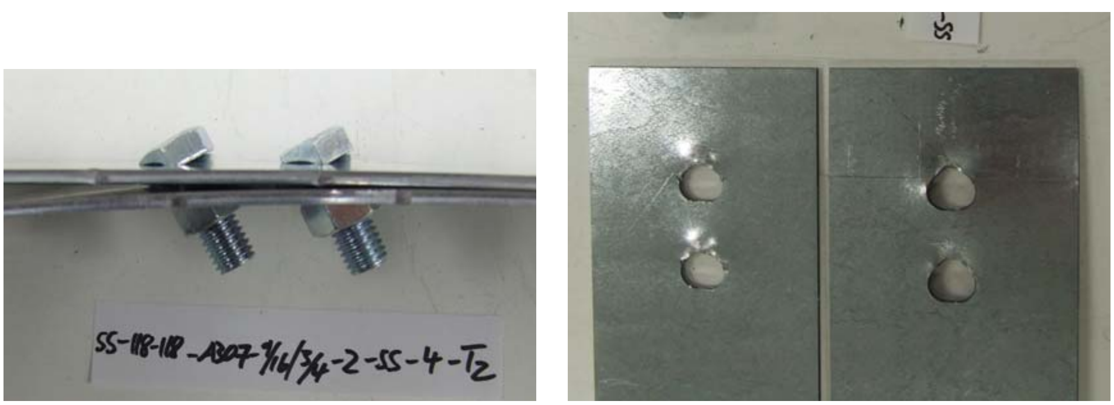


Fig 8-21 Failure Mode of Test SS-118-118-A307-9/16x3/4-2-SS-4-T2

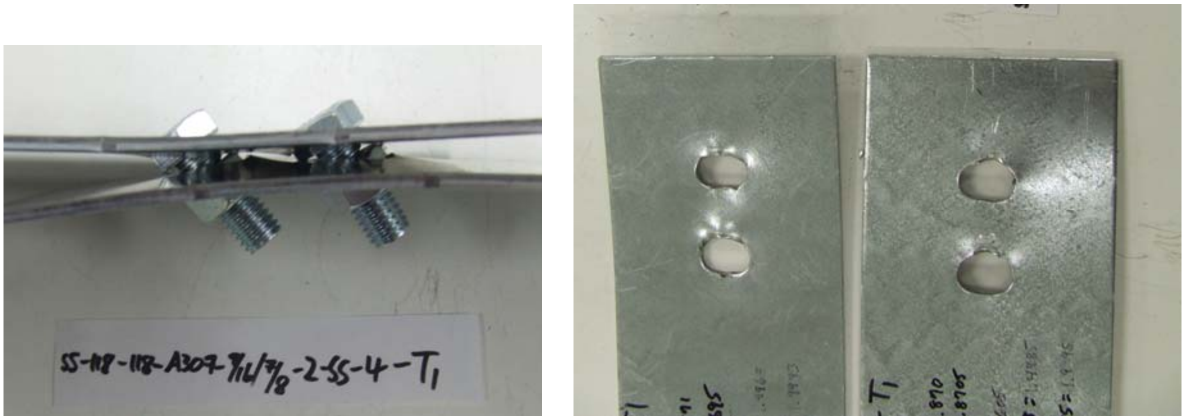


Fig 8-22 Failure Mode of Test SS-118-118-A307-9/16x7/8-2-SS-4-T1

The use of two different thickness sheets in one connection was studied by single shear tests in bearing. The test results are listed in Tables 8-10 and 8-11. Figures 8-23 and 8-24 show the failure mode of the connections using two different sheets with one bolt and two bolts respectively. It was found that the thinner sheet had larger deformation at the slotted hole and the nut or bolt head went through the thinner sheet.

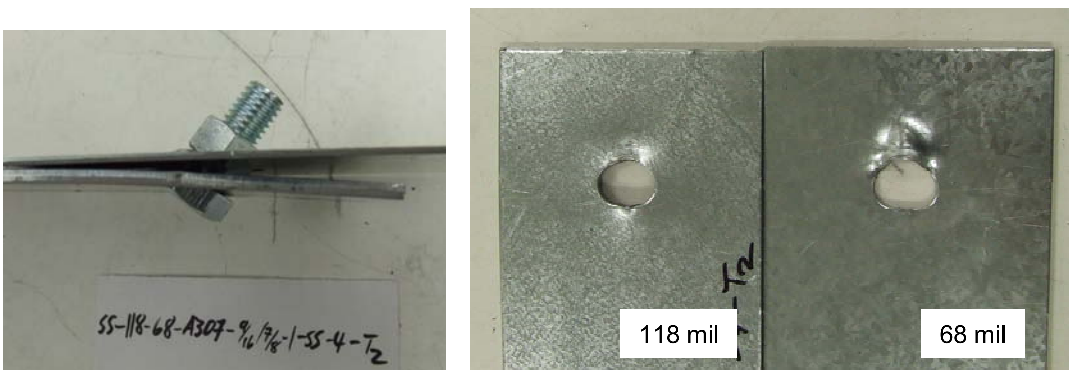


Fig 8-23 Failure Mode of Test SS-118-68-A307-9/16x7/8-1-SS-4-T2

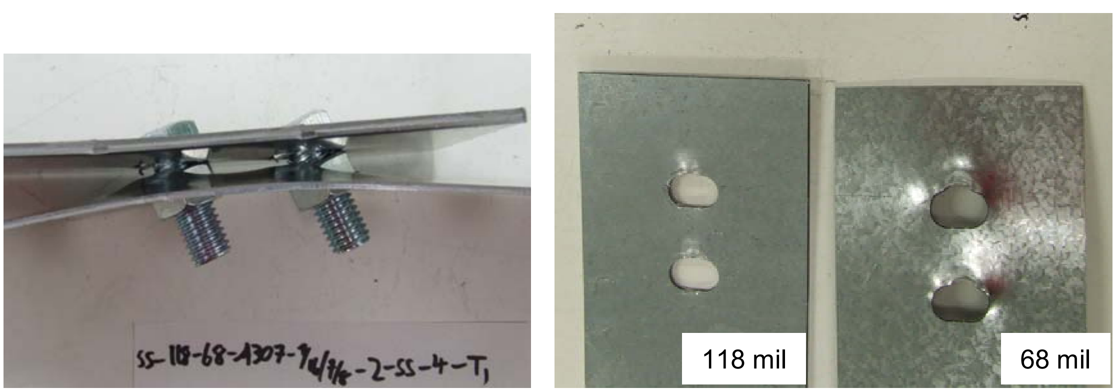


Fig 8-24 Failure Mode of Test SS-118-68-A307-9/16x7/8-2-SS-4-T1

Table 8-11 Test Results for Single Shear Connections with Slotted Holes, Single Bolt, e/d =4

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	SS-118-118-A307-9/16/3/4-1-SS-4-T1	118	118	0.5	3.83	52.2	6947	0.556	0.91
2	SS-118-118-A307-9/16/3/4-1-SS-4-T2	118	118	0.5	3.83	52.2	6810	0.649	0.89
3	SS-118-118-A307-9/16/7/8-1-SS-4-T1	118	118	0.5	3.83	52.2	5978	0.536	0.78
4	SS-118-118-A307-9/16/7/8-1-SS-4-T2	118	118	0.5	3.83	52.2	5393	0.492	0.70
5	SS-68-68-A307-9/16/3/4-1-SS-4-T1	68	68	0.5	7.16	54.5	2961	0.681	0.69
6	SS-68-68-A307-9/16/3/4-1-SS-4-T2	68	68	0.5	7.16	54.5	2906	0.695	0.68
7	SS-68-68-A307-9/16/3/4-1-SS-4-T3	68	68	0.5	7.16	54.5	2463	0.202	0.58
8	SS-68-68-A307-9/16/3/4-1-SS-4-T4	68	68	0.5	7.16	54.5	2683	0.196	0.63
9	SS-68-68-A307-9/16/7/8-1-SS-4-T1	68	68	0.5	7.16	54.5	2379	0.350	0.56
10	SS-68-68-A307-9/16/7/8-1-SS-4-T2	68	68	0.5	7.16	54.5	2270	0.367	0.53
11	SS-118-68-A307-9/16/3/4-1-SS-4-T1	118	68	0.5	7.16	52.2	5583	0.575	1.30
12	SS-118-68-A307-9/16/3/4-1-SS-4-T2	118	68	0.5	7.16	52.2	5425	0.607	1.27
13	SS-118-68-A307-9/16/7/8-1-SS-4-T1	118	68	0.5	7.16	52.2	3911	0.446	0.91
14	SS-118-68-A307-9/16/7/8-1-SS-4-T2	118	68	0.5	7.16	52.2	4284	0.523	1.00

Table 8-12 Test Results for Single Shear Connections with Slotted Holes, Double Bolts, e/d =4

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	SS-118-118-A307-9/16/3/4-2-SS-4-T1	118	118	0.5	3.83	52.2	5941	1.106	0.78
2	SS-118-118-A307-9/16/3/4-2-SS-4-T2	118	118	0.5	3.83	52.2	5699	0.693	0.74
3	SS-118-118-A307-9/16/7/8-2-SS-4-T1	118	118	0.5	3.83	52.2	5297	0.612	0.69
4	SS-118-118-A307-9/16/7/8-2-SS-4-T2	118	118	0.5	3.83	52.2	5246	0.672	0.68
5	SS-68-68-A307-9/16/3/4-2-SS-4-T1	68	68	0.5	7.16	54.5	2830	0.472	0.66
6	SS-68-68-A307-9/16/3/4-2-SS-4-T2	68	68	0.5	7.16	54.5	2768	0.478	0.65
7	SS-68-68-A307-9/16/7/8-2-SS-4-T1	68	68	0.5	7.16	54.5	2013	0.204	0.47
8	SS-68-68-A307-9/16/7/8-2-SS-4-T2	68	68	0.5	7.16	54.5	2247	0.426	0.52
9	SS-68-68-A307-9/16/7/8-2-SS-4-T3	68	68	0.5	7.16	54.5	2095	0.402	0.49
10	SS-118-68-A307-9/16/3/4-2-SS-4-T1	118	68	0.5	7.16	52.2	4528	0.566	1.10
11	SS-118-68-A307-9/16/3/4-2-SS-4-T2	118	68	0.5	7.16	52.2	4776	0.930	1.17
12	SS-118-68-A307-9/16/7/8-2-SS-4-T1	118	68	0.5	7.16	52.2	3472	0.473	0.85
13	SS-118-68-A307-9/16/7/8-2-SS-4-T2	118	68	0.5	7.16	52.2	4068	0.722	0.99

The bearing strength of bolted double shear connections without washers on short slotted holes were investigated through series of tests on 118 mil and 68 mil specimens using one and two ½:" diameter A307 bolts. The test results are summarized in Tables 8-13 and 8-14. Figure 8-25 illustrates the load vs. deformation curves for double shear tests with one bolt. Figure 8-26 through Figure 8-29 show the failure mode of typical 118 mil and 68 mil double shear tests with one bolt. In the double shear tests, the bolt remained perpendicular to the sheets therefore the load vs. deformation curves were much more smooth than the single shear tests. Typical bearing failure was observed on the inside sheet of double shear connections, the inside sheet contracted and piled up at the contact area with the bolt. For 118 mil tests, the bending of the bolt was observed along with the sheet bearing failure. Both 118 mil and 68 mil specimens failed in the same mode and 118 mil specimens yielded slightly higher strength than 68 mil specimens, but the difference was small.

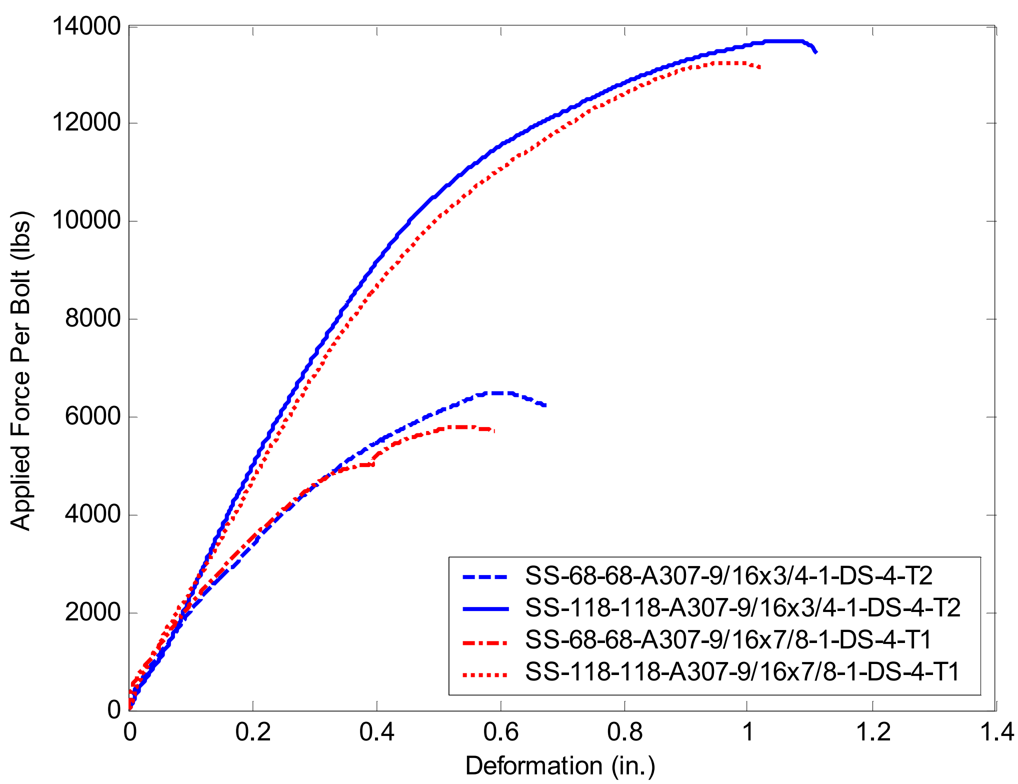


Fig 8-25 Load vs. Deformation Curves for Single Shear Connections with Single Bolt, Slotted Holes in Bearing,

Fig 8-26 Failure Mode of Test SS-68-68-A307-9/16x3/4-1-DS-4-T2

Fig 8-27 Failure Mode of Test SS-68-68-A307-9/16x7/8-1-DS-4-T1

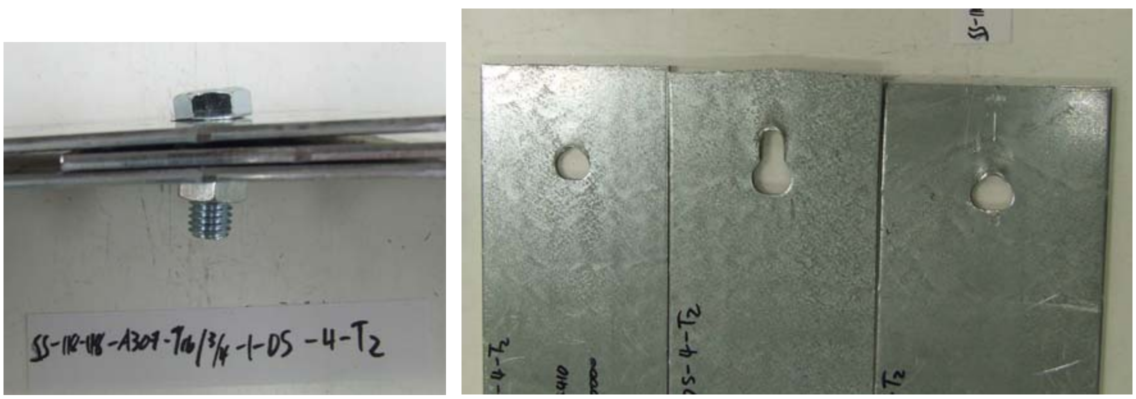


Fig 8-28 Failure Mode of Test SS-118-118-A307-9/16x3/4-1-DS-4-T2

Fig 8-29 Failure Mode of Test SS-118-118-A307-9/16x7/8-1-DS-4-T1

Table 8-13 Test Results for Double Shear Connections with Slotted Holes, Single Bolt, e/d =4

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NEW}
1	SS-118-118-A307-9/16/3/4-1-DS-4-T1	118	118	0.5	3.83	52.2	11994	1.087	1.05
2	SS-118-118-A307-9/16/3/4-1-DS-4-T2	118	118	0.5	3.83	52.2	13691	1.039	1.20
3	SS-118-118-A307-9/16/3/4-1-DS-4-T3	118	118	0.5	3.83	52.2	13417	0.994	1.17
4	SS-118-118-A307-9/16/7/8-1-DS-4-T1	118	118	0.5	3.83	52.2	13251	0.972	1.16
5	SS-118-118-A307-9/16/7/8-1-DS-4-T2	118	118	0.5	3.83	52.2	12751	0.862	1.11
6	SS-68-68-A307-9/16/3/4-1-DS-4-T1	68	68	0.5	7.16	54.5	5844	0.547	0.93
7	SS-68-68-A307-9/16/3/4-1-DS-4-T2	68	68	0.5	7.16	54.5	6507	0.594	1.03
8	SS-68-68-A307-9/16/3/4-1-DS-4-T3	68	68	0.5	7.16	54.5	6496	0.682	1.03
9	SS-68-68-A307-9/16/7/8-1-DS-4-T1	68	68	0.5	7.16	54.5	5790	0.529	0.92
10	SS-68-68-A307-9/16/7/8-1-DS-4-T2	68	68	0.5	7.16	54.5	5935	0.683	0.94

Table 8-14 Test Results for Double Shear Connections with Slotted Holes, Double Bolts, e/d =4

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NEW}
1	SS-68-68-A307-9/16/3/4-2-DS-4-T1	68	68	0.5	7.16	54.5	5058	0.855	0.80
2	SS-68-68-A307-9/16/3/4-2-DS-4-T2	68	68	0.5	7.16	54.5	4620	0.735	0.73
3	SS-68-68-A307-9/16/7/8-2-DS-4-T1	68	68	0.5	7.16	54.5	5173	0.755	0.82
4	SS-68-68-A307-9/16/7/8-2-DS-4-T2	68	68	0.5	7.16	54.5	5004	0.784	0.80

8.4.2 Sheet Shear Failure

The sheet shear failure of the bolted connections without washers on short slotted holes was studied by series of tests on single shear and double shear specimens with one ½” diameter A307 bolt, e/d = 1.5. Figure 8-30 illustrates the load vs. deformation curves of 118 mil and 68 mil single shear connections in the sheet shear failure. Figure 8-31 through 8-33 show the failure modes of the specimens in Figure 8-30. It was found that the bolt tilted greatly in the single shear tests in the shear failure. The bolt head and nut passed through the slots, and the sheets separated at peak loads. The connections with smaller slot sizes (9/16” × 3/4”) yield higher shear strength than the connections with larger slot sizes (9/16” × 7/8”).

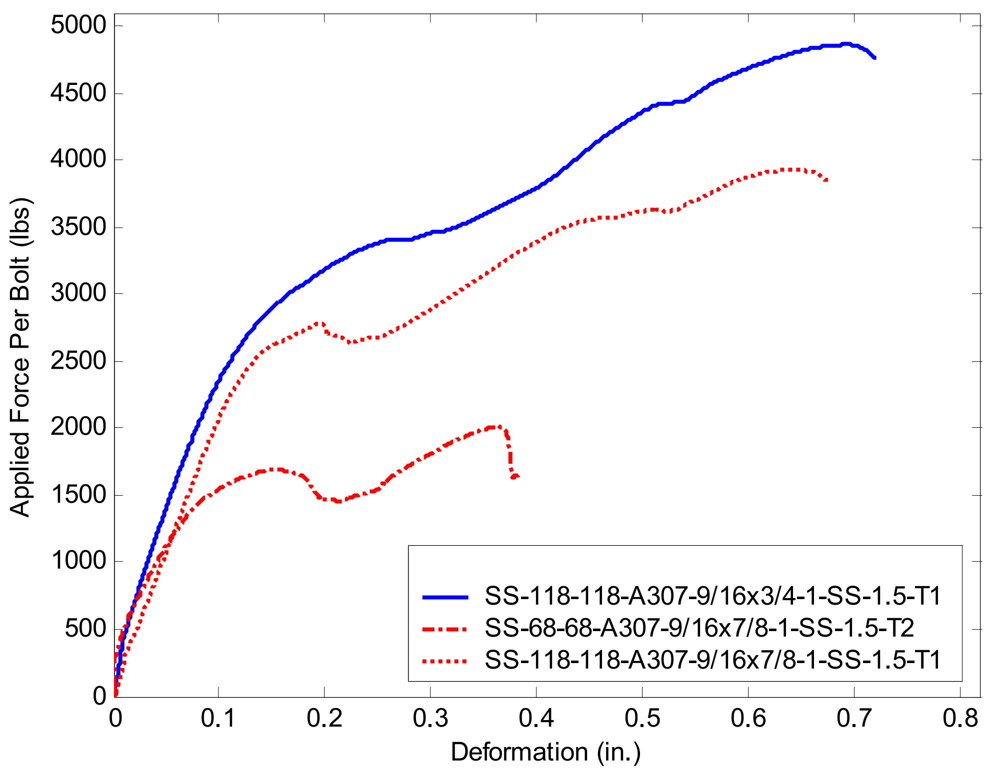


Fig 8-30 Load vs. Deformation Curves for Single Shear Connections with Single Bolt, Slotted Holes, in Shear

Fig 8-31 Failure Mode of Test SS-118-118-A307-9/16x3/4-1-SS-1.5-T1

Fig 8-32 Failure Mode of Test SS-118-118-A307-9/16x7/8-1-SS-1.5-T1

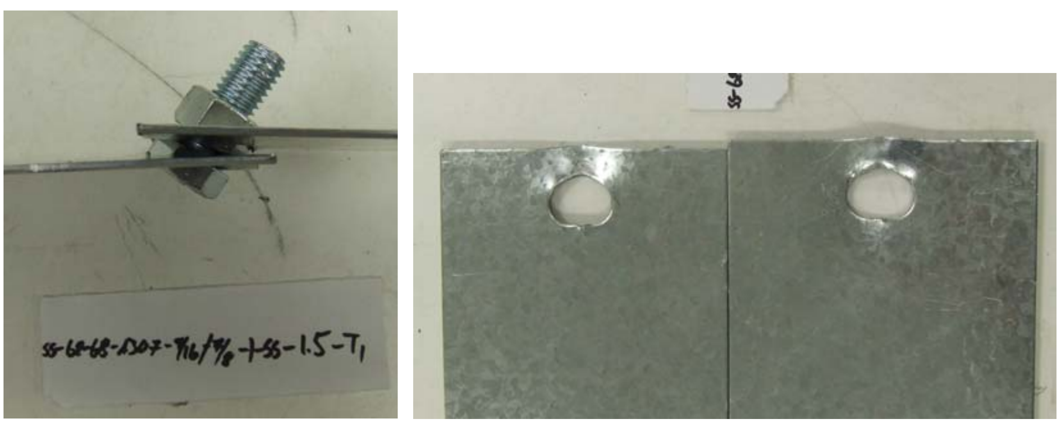


Fig 8-33 Failure Mode of Test SS-68-68-A307-9/16x7/8-1-SS-1.5-T1

The sheet shear failure of the bolted connections without washers on short slotted holes was studied by series of tests on single shear and double shear specimens with one ½” diameter A307 bolt, e/d = 1.5. Figure 8-30 illustrates the load vs. deformation curves of 118 mil and 68 mil single shear connections in the sheet shear failure. Figure 8-34 illustrates the load vs. deformation curves for double shear tests in sheet shear failure. Figures 8-35 through 8-38 show the failure mode of the specimens presented in Figure 8-34. It was found that the bolt in all double shear tests remained perpendicular to the sheets, no bolt tilting occurred during the tests, therefore the load vs. deformation curves were smooth. Typical sheet shear failure was achieved on the inside sheet of the double shear specimens. The sheet was extruded at the area in contact with the bolt. The connections with two different slot sizes demonstrated identical mode of failure. The connections with 9/16”×3/4” slot yielded slightly higher shear strength than the connections with 9/16”×3/4”, but the difference was small. The test results for the sheet shear failure are summarized in Tables 8-15 and 8-16 for single shear and double shear respectively.

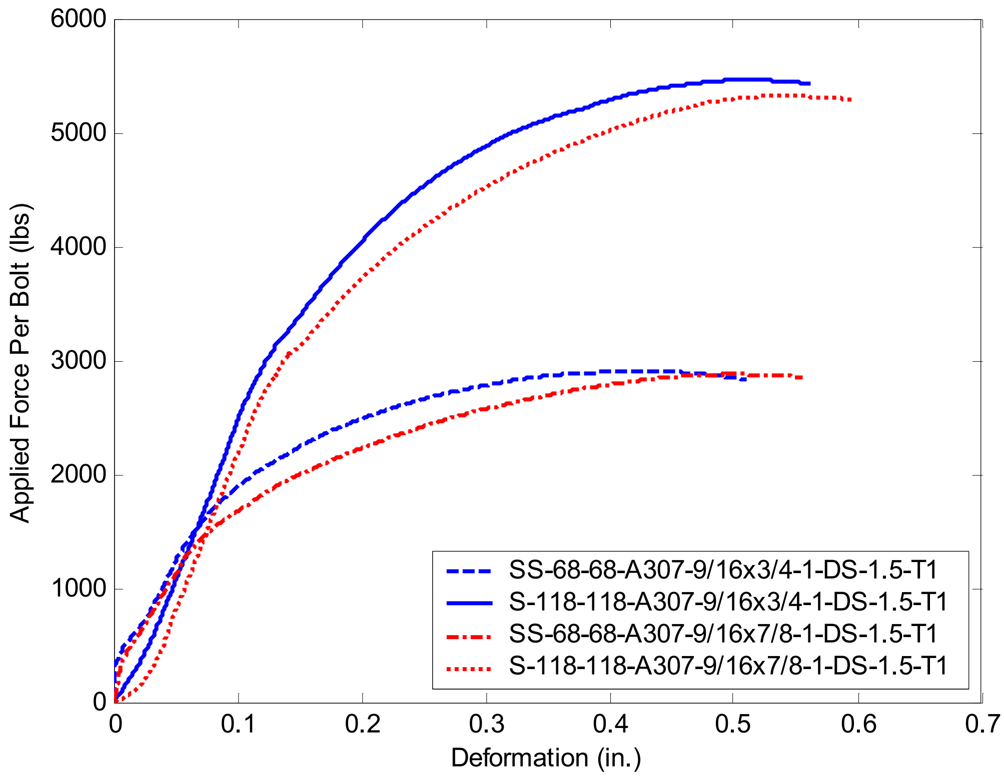


Fig 8-34 Load vs. Deformation Curves for Double Shear Connections with Single Bolt, Slotted Holes, in Shear

Fig 8-35 Failure Mode of Test SS-118-118-A307-9/16x3/4-1-DS-1.5-T1

Fig 8-36 Failure Mode of Test SS-118-118-A307-9/16x7/8-1-DS-1.5-T1

Fig 8-37 Failure Mode of Test SS-68-68-A307-9/16x3/4-1-DS-1.5-T1

Fig 8-38 Failure Mode of Test SS-68-68-A307-9/16x7/8-1-DS-1.5-T1

Table 8-15 Test Results for Single Shear Connections with Slotted Holes, Single Bolt, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	SS-118-118-A307-9/16/3/4-1-SS-1.5-T1	118	118	0.5	3.83	0.75	52.2	4861	0.689	0.95
2	SS-118-118-A307-9/16/3/4-1-SS-1.5-T2	118	118	0.5	3.83	0.75	52.2	4757	0.655	0.93
3	SS-118-118-A307-9/16/7/8-1-SS-1.5-T1	118	118	0.5	3.83	0.75	52.2	3924	0.633	0.77
4	SS-118-118-A307-9/16/7/8-1-SS-1.5-T2	118	118	0.5	3.83	0.75	52.2	3595	0.493	0.70
5	SS-68-68-A307-9/16/7/8-1-SS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2056	0.353	0.72
6	SS-68-68-A307-9/16/7/8-1-SS-1.5-T2	68	68	0.5	7.16	0.75	54.5	2013	0.363	0.71

Table 8-16 Test Results for Double Shear Connections with Slotted Holes, Single Bolt, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	SS-118-118-A307-9/16/3/4-1-DS-1.5-T1	118	118	0.5	3.83	0.75	52.2	5460	0.497	1.07
2	SS-118-118-A307-9/16/3/4-1-DS-1.5-T2	118	118	0.5	3.83	0.75	52.2	5441	0.503	1.06
3	SS-118-118-A307-9/16/7/8-1-DS-1.5-T1	118	118	0.5	3.83	0.75	52.2	5323	0.539	1.04
4	SS-118-118-A307-9/16/7/8-1-DS-1.5-T2	118	118	0.5	3.83	0.75	52.2	5302	0.547	1.04
5	SS-68-68-A307-9/16/3/4-1-DS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2903	0.430	1.02
6	SS-68-68-A307-9/16/3/4-1-DS-1.5-T2	68	68	0.5	7.16	0.75	54.5	2884	0.414	1.01
7	SS-68-68-A307-9/16/7/8-1-DS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2878	0.495	1.01
8	SS-68-68-A307-9/16/7/8-1-DS-1.5-T2	68	68	0.5	7.16	0.75	54.5	2717	0.464	0.95

8.4.3 Sheet Bearing Failure and Sheet Shear Failure Combined

The test matrix included series of tests on 68 mil single shear connections using two ½” diameter A307 bolts. The first bolt was placed close to the edge of the sheet with e/d = 1.5. The second bolt was placed 3 times of the bolt diameter (3d) from the center of the first bolt hole. Therefore the sheet shear failure was expected to occur at the first hole location and the sheet bearing failure was expected to happen at the second hole location. Figures 8-39 and 8-40 show the typical failure mode on single shear connections with 9/16”×3/4” slots and 9/16”×7/8” slots respectively. The bolts were tilted greatly in the tests and the nut and bolt head went through the slots which caused the separation of the two sheets. It was found that the connections with smaller slot sizes yielded higher strength than the connections with bigger slot sizes. The test results of this specific configuration are summarized in Table 8-17.

Fig 8-39 Failure Mode of Test SS-68-68-A307-9/16x3/4-2-SS-1.5-T3

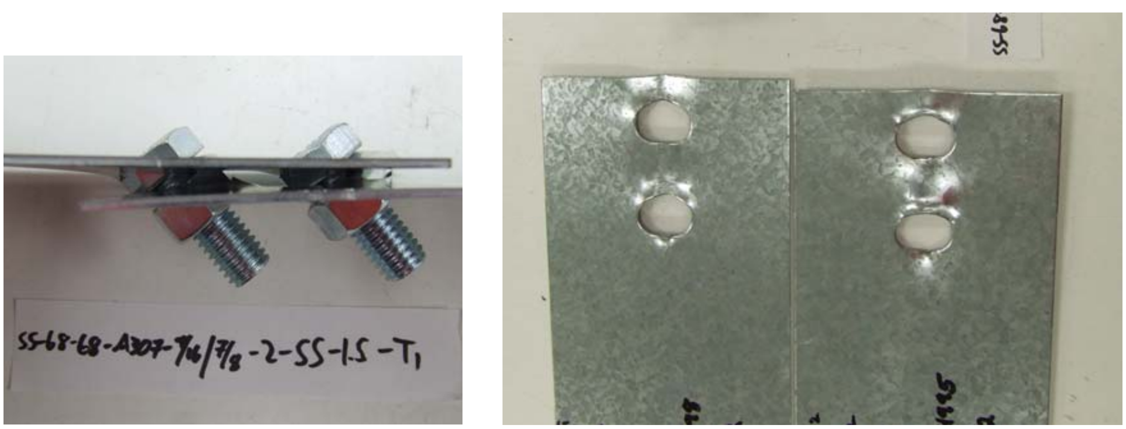


Fig 8-40 Failure Mode of Test SS-68-68-A307-9/16x7/8-2-SS-1.5-T1

Table 8-17 Test Results for Single Shear Connections with Slotted Holes, Double Bolts, e/d =1.5

No	Specimen Label	Nominal SHT(1) Thickness (mil)	Nominal SHT(2) Thickness (mil)	Bolt Dia. d (in.)	d/t	e (in.)	Actual F_u (ksi)	P_{test} (lbf)	Δ (in.)	P_{test}/P_{NAS}
1	SS-68-68-A307-9/16/3/4-2-SS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2260	0.298	
2	SS-68-68-A307-9/16/3/4-2-SS-1.5-T2	68	68	0.5	7.16	0.75	54.5	2577	0.511	
3	SS-68-68-A307-9/16/3/4-2-SS-1.5-T3	68	68	0.5	7.16	0.75	54.5	2615	0.494	
4	SS-68-68-A307-9/16/7/8-2-SS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2021	0.411	
5	SS-68-68-A307-9/16/7/8-2-SS-1.5-T2	68	68	0.5	7.16	0.75	54.5	1930	0.403	

9 DISCUSSION

9.1 SHEET BEARING STRENGTH OF BOLTED CONNECTIONS WITHOUT WASHERS ON OVERSIZED HOLES

The test results on connections with oversized holes and e/d > 3 were compared to the calculated bearing strength for bolted connections without washers on standard holes using NAS (2007). The current NAS (2007) uses two factors, modification factor m_f and bearing factor C, to account for different connections configurations. A unified bearing factor formula, listed in Table 5-2, is used in NAS (2007) for both single shear and double shear connections. For the modification factor, different values were adopted. For single shear connections without washer on standard hole, m_f = 0.75. For the inside sheet of double shear connections without washer, m_f = 1.33.

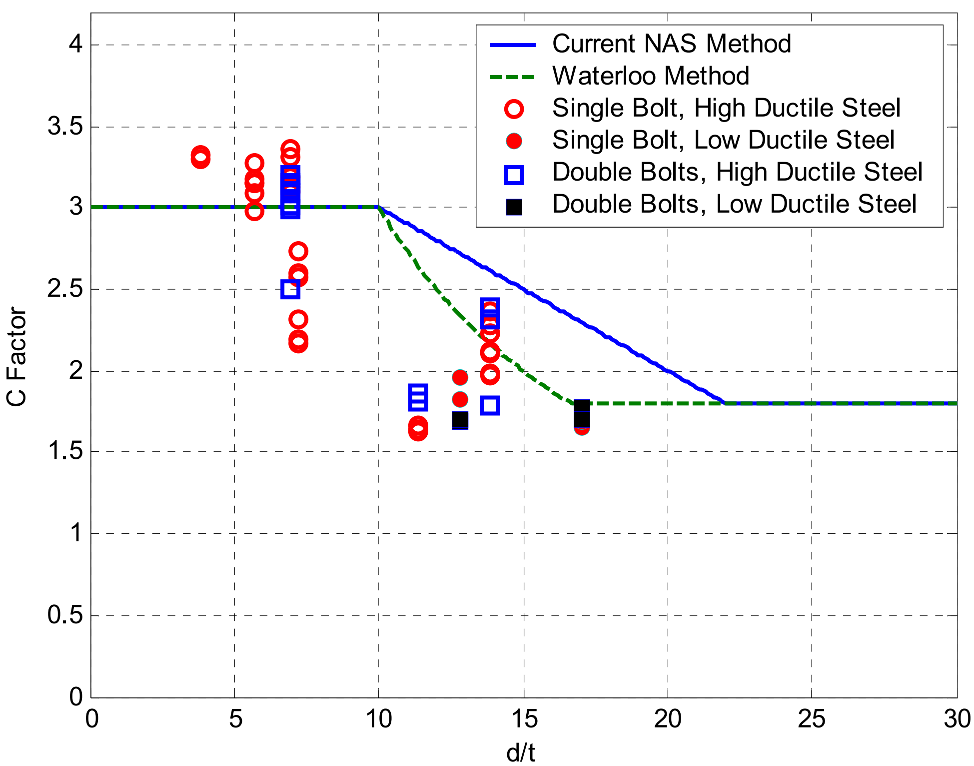


Fig 9-1 C vs d/t for Bearing Strength Test on Single Shear Connections with Oversized Holes

Figure 20 illustrates the comparison of the tested bearing factor C with the NAS and Waterloo C equations for single shear connections. The tested bearing factor C is calculated by using the equation $C = P_{test} / (m_f\ d\ t\ F_u)$, where m_f = 0.75. Figure 9-1 indicates that for single shear connections with d/t greater than 7, the tested bearing strength is systemically lower than the NAS predictions. And the majority of tests are also lower than the Waterloo predictions. Figure 9-1 also shows that the connections with single bolt have close bearing strength to the same connections using two bolts. In Figure 9-1, the low ductile steel connections are labeled using solid symbols which are all located at the bottom of the whole data pool but still within the boundary. It indicates that the low ductile steel and high ductile steel connections can be treaded equally in terms of predicting the bearing strength.

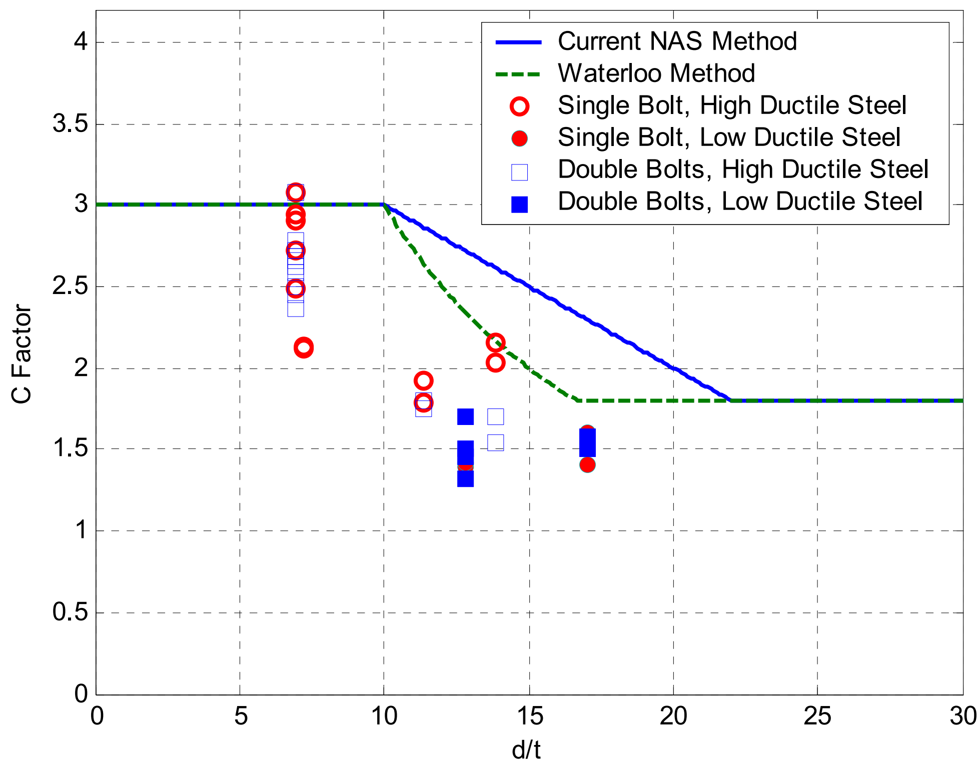


Fig 9-2 C vs d/t for Bearing Strength Test on Double Shear Connections with Oversized Holes

Figure 9-2 provides a comparison on the bearing factor C for double shear connections. In this comparison, the tested bearing factors were calculated by the same equation for single shear connection but using m_f = 1.33. Similar to the findings for single shear connections, the majority of the double shear connections with oversized holes yielded consistently lower bearing strength than the NAS and Waterloo predictions for connections with standard holes. The tested bearing factors for single and double bolt connections are close. The low ductile steel connections have a lower tested bearing factor than the high ductile steel connections, but the difference is not significant enough to distinguish the two types of steel into two trends.

In general, the test results indicate that the cold-formed steel bolted connections without washers on oversized holes yield systematically and significantly lower bearing strength than the predicted values by the current NAS and Waterloo methods for connections without washers on standard holes. The test-to-NAS prediction ratios are listed in Tables 8-2, 8-3, 8-4, and 8-5. On average, the test-to-predicted ratio for the sheet bearing strength is 0.87 for single shear connections and 0.75 for double shear connections. Tables 9-1 and 9-2 summarize the average ratio for the overall tests and breakdowns according to the number of bolts and the steel ductility.

Table 9-1 Test-to-Predicted Ratios for Sheet Bearing Strength of Single Shear Connections with Oversized Holes

Connection configuration	Number of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW}		
		Average	Standard deviation	Coefficient of variation	Average	Standard deviation	Coefficient of variation
Single bolt	34	0.88	0.17	0.194	1.02	0.14	0.135
Double bolts	17	0.84	0.17	0.206	1.00	0.13	0.127
High ductile steel	43	0.90	0.17	0.187	1.03	0.14	0.134
Low ductile steel	8	0.70	0.06	0.081	0.93	0.07	0.069
Overall	51	0.87	0.17	0.198	1.01	0.13	0.131

Table 9-2 Test-to-Predicted Ratios for Sheet Bearing Strength of Double Shear Connections with Oversized Holes

Connection configuration	Number of tests	P_{test}/P_{NAS}			P_{test}/P_{NEW}		
		Average	Standard deviation	Coefficient of variation	Average	Standard deviation	Coefficient of variation
Single bolt	17	0.77	0.16	0.215	1.03	0.15	0.147
Double bolts	20	0.74	0.16	0.209	0.98	0.10	0.105
High ductile steel	26	0.82	0.13	0.163	1.05	0.11	0.109
Low ductile steel	11	0.59	0.08	0.126	0.90	0.10	0.114
Overall	37	0.75	0.16	0.210	1.00	0.13	0.127

Based on the test results for the bearing strength, new bearing factor, C, and modification factor, m_f, are proposed to better predict the bearing strength of cold-formed steel connections without washers on oversized holes. Table 9-3 and Table 9-4 respectively summarize the proposed factors for the single and double shear connections. The same bearing strength equation (Eq. 6.2) used in NAS (2001) will be still employed for connections with oversized holes but the factors will be replaced by the newly proposed ones.

Table 9-3 Proposed Bearing Factor, C, for Bolted Connections with Oversized Holes

Ratio of fastener diameter to member thickness, d/t	C
$d/t < 7$	3
$7 \le d/t \le 18$	$1+14/(d/t)$
$d/t > 18$	1.8

Table 9-4 Proposed Modification Factor, m_f, for Bolted Connections with Oversized Holes

Type of bearing connection	m_f
Single shear connection without washers under both bolt head and nut on oversized hole	0.72
Inside sheet of double shear connection without washers on oversized hole	1.12

Figures 9-3 and 9-4 show the comparison between the test results and the two design methods for the single shear and double shear connections respectively. In the figures, the y-axis is the $P/(F_u\ d\ t)$ where P represents the nominal bearing strength for the design methods and it stands for the peak load per bolt for the test results. Figures 9-3 and 9-4 demonstrate that the proposed design method has a good agreement with the test results for both single and double shear bearing connections. The average test-to-predicted ratio for the proposed method is 1.01 for the single shear connections and 1.00 for the double shear connections. A standard deviation of 0.13 is achieved for both types of connections. It is also suggested that the newly proposed design method be applicable for both low and high ductile steel connections.

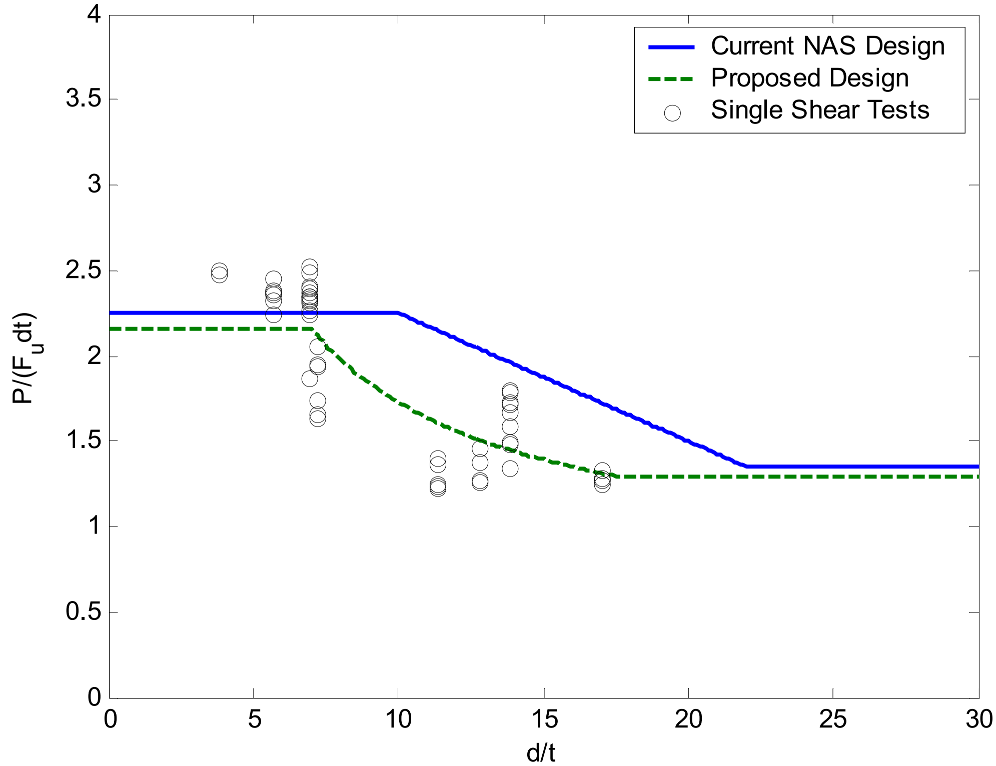


Fig 9-3 Test Results vs. Design Methods for Single Shear Connections with Oversized Holes

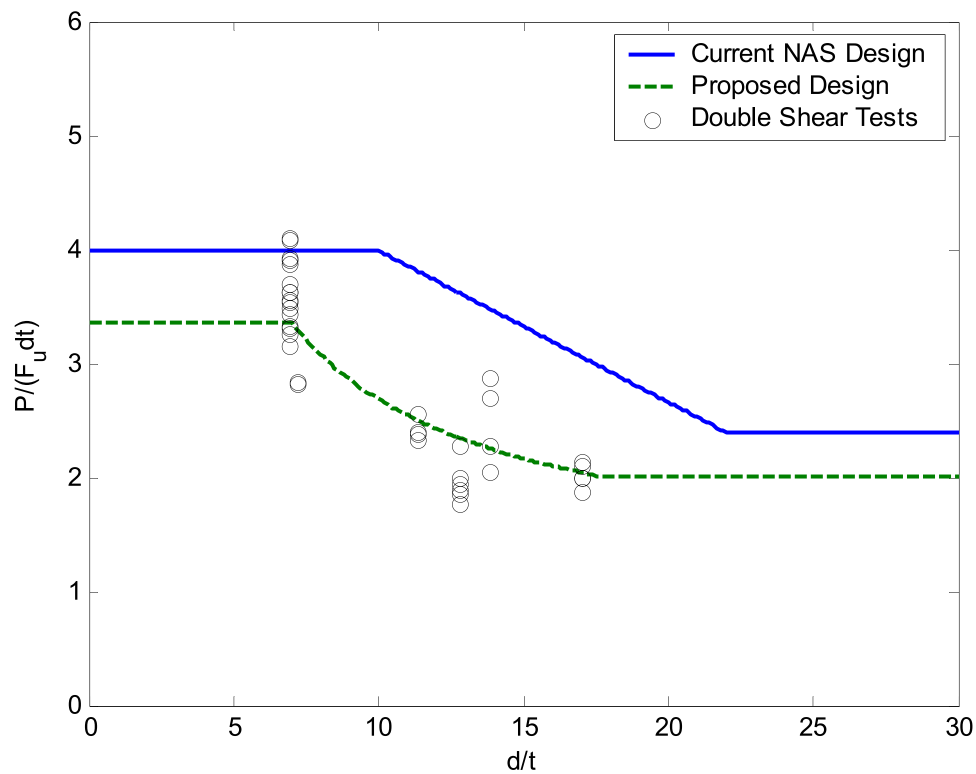


Fig 9-4 Test Results vs. Design Methods for Double Shear Connections with Oversized Holes

For the proposed bearing strength method, the resistance factors, ϕ, for LRFD and LSD design method and the safety factor, Ω, for ASD design method were determined in accordance with Chapter F of NAS (2007). Table 9-5 summarizes the results.

Table 9-5 Resistance Factors and Factors of Safety for Bolted Connections in Bearing

	Single Shear Connections without Washers on Oversized Holes	Inside Sheet of Double Shear Connection without Washers on Oversized Holes
Quantity	51	37
Mean	1.01	1.00
St. Dev	0.13	0.13
C.O.V.	0.131	0.127
M_m	1.10	1.10
V_m	0.08	0.08
F_m	1.00	1.00
P_m	1.01	1.00
V_f	0.05	0.05
β_o (LRFD)	3.5	3.5
β_o (LSD)	4.0	4.0
V_Q	0.21	0.21
ϕ (LRFD)	0.664	0.660
ϕ (LSD)	0.543	0.540
Ω (ASD)	2.411	2.424

9.2 SHEET SHEAR STRENGTH OF BOLTED CONNECTIONS WITHOUT WASHERS ON OVERSIZED HOLES

The current NAS (2007) uses a unified equation (Eq. 5.1) for the sheet shear strength for all bolted connections with standard holes. The test-to-NAS prediction ratio for each shear strength test is listed in Tables 8-6 and 8-7. Figure 9-5 illustrates a comparison of the tested shear strengths with the NAS (2007) predictions (Eq. 5.1). The plot indicates that the current NAS provisions for the sheet shear strength of bolted connections on standard holes have a good agreement with the test results for connections without washer on oversized holes. The average ratio of P_{test} to P_{NAS} for all tests is 1.05 with a standard deviation of 0.22. No significant difference was found between the single and double shear connections in terms of the sheet shear strength. The NAS (2007) gives fairly good prediction for the sheet shear strength for low ductile steel connections. The average test-to-predicted ratio for the low ductile steel is 0.93 with a standard deviation of 0.11. Overall, the current NAS design method can be extended to the bolted connections without washers on oversized holes. The details of the test-to-predicted ratios are summarized in Table 9-6.

Table 9-6 Test-to-Predicted Ratios for Sheet Shear Strength of Connections with Oversized Holes

Connection configuration	Number of tests	P_{test}/P_{NAS}		
		Average	Standard deviation	Coefficient of variation
Single shear	31	1.01	0.20	0.200
Double shear	24	1.10	0.24	0.214
High ductile steel	26	1.06	0.21	0.194
Low ductile steel	19	0.93	0.11	0.120
Overall	55	1.05	0.22	0.210

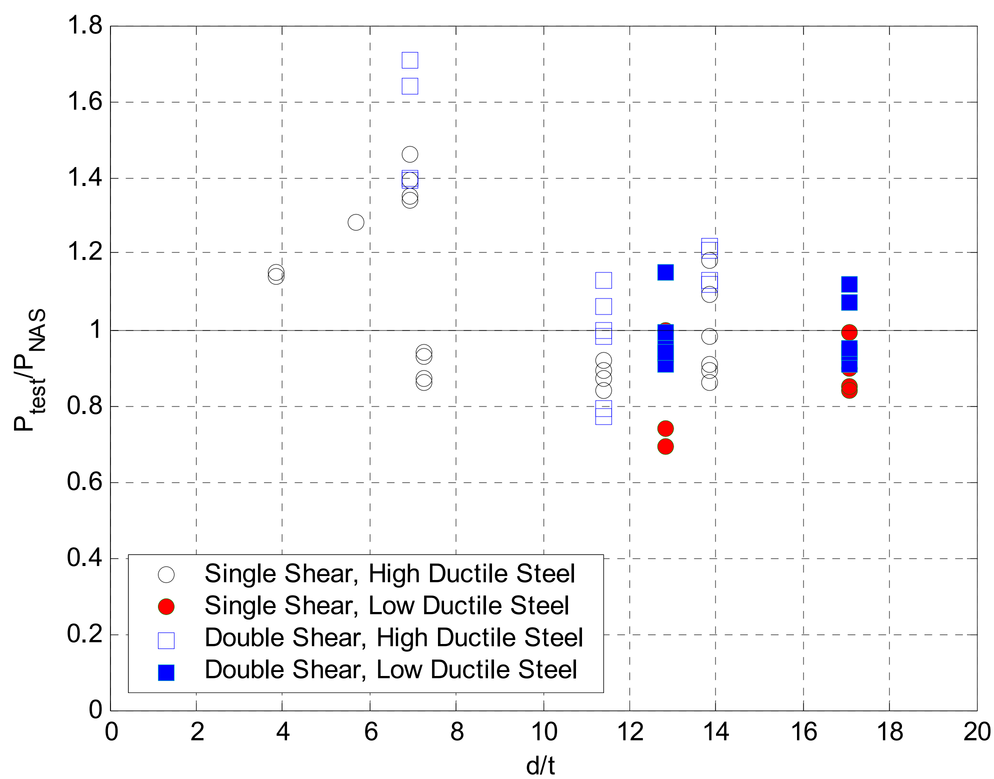


Fig 9-5 P_{test}/P_{NAS} Vs d/t for Sheet Shear Strength of Connections with Oversized Holes

9.3 LOW DUCTILE VS HIGH DUCTILE STEEL

Figures 9-1 and 9-2 illustrate comparisons of the bearing strength tests with the design equations for single shear and double shear respectively. In the figures, solid symbols are used for the low ductile steel tests to distinguish them form the other high ductile steel tests. In both figures the low ductile steel data points are located on the lower bound of the whole test point set but are not separate from the main group. The comparison indicates that the low ductility in the material did not significantly weaken the bearing strength of the bolted connections. For the sheet shear strength, the same conclusion can be made as it is shown in Figure 9-5 that the low ductile steel tests (30 mil and 39 mil) give a good agreement with the NAS predictions which was originally developed for high ductile steel connections. As mentioned in the previous sections, the proposed bearing strength method and the current NAS sheet shear strength method work well for low ductile steel.

It was also observed that the low ductile steel connections had less hole elongation than that in the high ductile steel at peak loads. As a result, the tilting of the bolt in the low ductile steel connections was less than in the high ductile steel single shear connections. Figure 9-6 shows the bearing failure of a 43 mil high ductile steel connection and Figure 9-7 shows the bearing failure of a 39 mil low ductile steel connection. The high ductile steel sheet warped greatly and the elongation of the hole was large enough to allow the head of the bolt to pass through the sheet. The low ductile steel connections had similar behaviors; the bolt tilted and in some tests, the bolt head and nut penetrated the sheet through the hole. In general the low ductile steel sheets demonstrated less warping and hole deformation than the high ductile steel sheets.

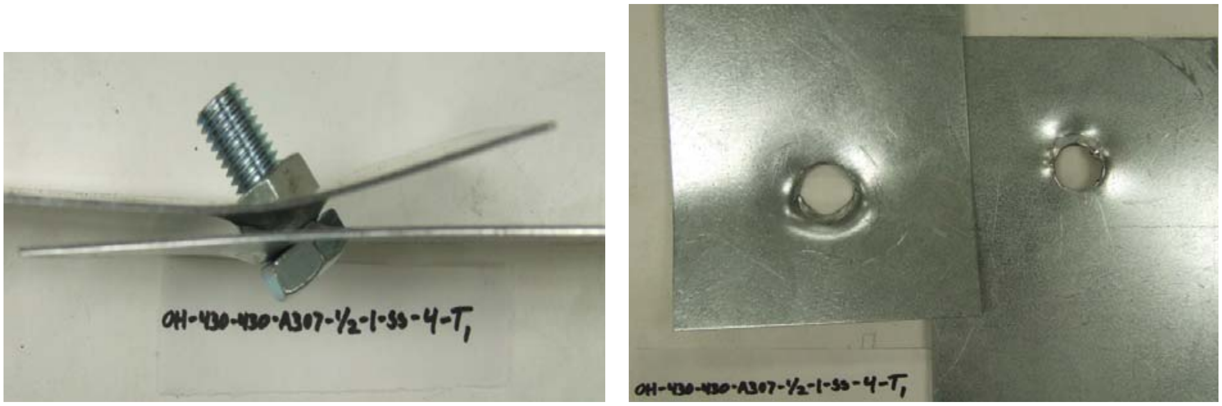


Fig 9-6 43 mil High Ductile Steel Bearing Failure

Fig 9-7 39 mil Low Ductile steel Bearing Failure

9.4 A307 VS A325 BOLTS

A325 bolts and the A307 Type A bolts both have the same nominal shank diameter (1/2”), however, the A325 bolt has larger head and nut size (measured side to side dimension 0.862”) that that of the A307 Type A bolt (measured side to side value 0.739”). The use of ASTM A307 Type A and A325 bolts was investigated by the tests on 68 mil single shear connections using one ½” diameter bolt. The test results are listed in Tables 8-5 and 8-6. Table 9-7 summarizes and compares the 68 mil tests with two types of bolts for bearing strength. The results indicate that connections with A325 bolt yielded reasonably higher bearing strength (average 18% higher) than those using A307 bolts. Since the bolt head and nut have partial function as washers in the bolted connections, the larger size of head and nut in A325 bolt help to reduce the tilting of the bolt as well as the curling of the sheet, thus resulting in a higher bearing strength. Figures 9-8 and 9-9 show bearing failures of single shear connections using A307 and A325 bolt respectively. It can be seen that the A325 bolt ended up with less rotation than the A307 bolt. The use of A325 bolt is more beneficial for bearing strength in single shear connections without washers.

Table 9-8 summarizes the 68 mil tests with two types of bolts for sheet shear strength. The results show that the A325 bolt connections yielded slightly higher sheet shear strength than the A307 bolt connections with an average 8% increase. Figure 9-10 and Figure 9-11 respectively shows the sheet shear failure mode of 68 mil single shear connections with A307 bolt and A325 bolt. It was found that the A307 bolt tilted greatly in single shear and the sheet warped. The A325 bolt achieved typical sheet shear failure in the sheet and the bolt tilted as well but not as significantly as the A307 bolt did.

Overall, the use of A325 bolt will increase the bearing strength and sheet strength of single shear bolt connections due to larger head and nut sizes compared to the A307 Type A bolt with the same nominal bolt diameter. The tests show that the improvement is greater in the bearing strength. The proposed design method for bearing strength is calibrated by the tests on A307 bolts and is therefore conservative for connections using A325 bolts.

Table 9-7 Comparison in Bearing Strength between A307 and A325 Bolts

Test label	Bolt Type - Diameter	Connection Configuration	P_{test} (lbs)	Average P_{test} (lbs)
OH-68O-68O-A325-1/2-1-SS-4-T1	A325 - 1/2“	Single Shear	4685	4760
OH-68O-68O-A325-1/2-1-SS-4-T2	A325 - 1/2“	Single Shear	4945	
OH-68O-68O-A325-1/2-1-SS-4-T3	A325 - 1/2“	Single Shear	4649	
OH-68O-68O-A307-1/2-1-SS-4-T1	A307 - 1/2”	Single Shear	3971	4026
OH-68O-68O-A307-1/2-1-SS-4-T2	A307 - 1/2“	Single Shear	3925	
OH-68O-68O-A307-1/2-1-SS-4-T3	A307 - 1/2“	Single Shear	4182	

Fig 9-8 Bearing Failure of a 68 mil Single Shear Connection with One A307 Bolt

Fig 9-9 Bearing Failure of a 68 mil Single Shear Connection with One A325 Bolt

Table 9-8 Comparison between 1/2" Dia. A307 and A325 Bolts in Single Shear

Test Label	P_{test} (lbs)	Average P_{test} (lbs)
OH-68O-68O-A325-1/2-1-SS-1.5-T1	3404	3384
OH-68O-68O-A325-1/2-1-SS-1.5-T2	3363	
OH-68O-68O-A307-1/2-1-SS-1.5-T1	3134	3123
OH-68O-68O-A307-1/2-1-SS-1.5-T2	3112	

Fig 9-10 Sheet Shear Failure of a 68 mil Single Shear Connection with One A307 Bolt

Fig 9-11 Sheet Shear Failure of a 68 mil Single Shear Connection with One A325 Bolt

9.5 CONNECTIONS WITH DIFFERENT SHEETS AND DIFFERENT HOLE SIZES

The option to use different sheet thicknesses and hole sizes in one bolted connection sheets was studied by tests on 33 mil single shear connections without washer using one ½" diameter A307 bolt. The results are summarized in Table 9-9 and it indicates that the use of a standard hole on one sheet and oversized hole on the other sheet may increase the bearing strength of the connection. Use of thicker material on one sheet can also improve the bearing strength of the connection. The improvement in the bearing strength by using higher strength configurations in one connected sheet can be achieved but the increase in strength is not significant. It is recommended that the connection strength be calculated according to the weaker sheet configuration.

Table 9-9 Comparison among for 33 mil Single Shear Connections Using One 1/2" Dia. A307 Bolt

Connection Configurations without washers	Average P_{test} (lbs)	Bearing Strength Increased
33 mil oversized holes	1448	0%
33 mil oversized/standard holes	1544	6.6%
33 mil standard holes	1586	9.6%
33 mil 43 mil oversized holes	1653	14.2%

9.6 TWO-BOLT CONNECTIONS WITH OVERSIZED HOLES IN BEARING AND SHEAR COMBINED FAILURE

The main test group had specific configurations in two-bolt connections which demonstrated shear failure at the hole nearest to the sheet edge and experienced bearing failure at the other hole. The test results and failure mode have been discussed in Section 8.2.3. Tables 9-10 and 9-11 compare the peak loads of the combined failure to the typical bearing failures in two-bolt connections and the typical shear failure in one-bolt connections in single shear and double shear respectively. In order to make the values comparable, the P_{test} in both tables is the average peak load per bolt. It was found that for the high ductile steel connections, the peak load of the combined failures is greater than sheet shear failure and less than the bearing failure. When the bearing strength is significantly higher than the shear strength, the strength of the combined failures is closer to the shear strength. The load distribution between the two bolts in the specific connection configuration is complicated and need further investigation. It is recommended to use sheet strength for both bolts to predict the connection strength for this specific configuration.

Table 9-10 Comparison between Combined Failure and Typical Failures for Single Shear

Connection Configuration	P_{test} (lbs)			
	One Bolt, Sheet Shear Failure (P_1)	Two Bolt, Combined Failures (P_2)	Two Bolts, Bearing Failure (P_3)	$\frac{(P_1+P_3)}{2}$
43 mil, 1/2" A307	2004	2071	2127	2066
33 mil, 1/2" A307	1281	1386	1308	1295
33 mil, 1/4" A307	1001	1030	1103	1052
30 mil, 1/2” A307	1724	1712	1667	1696
39 mil, 1/2” A307	2537	1902	2241	2389

Table 9-11 Comparison between Combined Failure and Typical Failures for Double Shear

Connection Configuration	P_{test} (lbs)			
	One Bolt, Sheet Shear Failure (P_1)	Two Bolt, Combined Failures (P_2)	Two Bolts, Bearing Failure (P_3)	$\frac{(P_1 + P_3)}{2}$
43 mil, 1/2" A307	1962	2470	3646	2804
33 mil, 1/2" A307	1648	1777	2110	1879
33 mil, 1/4" A307	1020	1225	1717	1369
30 mil, 1/2" A307	1773	2002	2617	2159
39 mil, 1/2" A307	2662	2562	3523	3093

9.7 OPTIONS OF WASHERS AND HOLE SIZES (ADDITIONAL GROUP)

The aim of this additional group tests is to identify the difference in bearing strength between oversized and standard holes as well as between the "with washer" and "without washer" options. The test results are listed in Table 8-10 where P_{NAS} is the bearing strength determined by the current NAS (2007) method for connections with standard holes.

The tests on connections with standard holes in the additional group are compared with the previous tests conducted by other researchers. Wallace, LaBoube, Schuster (2001) summarized previously conducted tests and use the data to calibrate the current NAS Method. Figure 9-12 shows a comparison between the previous tests and the tests of this research on 33 mil and 43 mil single shear connections with washers on standard holes. It shows that the tests of this research have a good match to the previous data for single shear connections with washers on standard holes. Figure 9-13 illustrates a similar comparison to Figure 9-12 but on the "without washer" option. Figure 9-13 indicates that the tests of this research on connections without washers on standard holes stay at the bottom of the previous test data pool but do not exceed the boundary limits.

The direct comparison between the additional group and the main group tests on the 33 mil and 43 mil single shear connections indicate that the connections with oversized holes yield less bearing strength than those with standard holes for both “with washer” and “without washer” configurations. Table 9-12 summarizes the ratios of bearing strength of connections with oversized holes to connections with standard holes. The reduction in the bearing strength can be as large as 20% for single shear connections.

Table 9-12 Direct Comparison between Tests on Connections with Oversized holes and Standard Holes in Bearing

Sheet Thickness	$P_{oversized\ hole}/P_{standard\ hole}$	
	Without Washers	With Washers
33 mil	0.924	0.838
43 mil	0.803	0.895

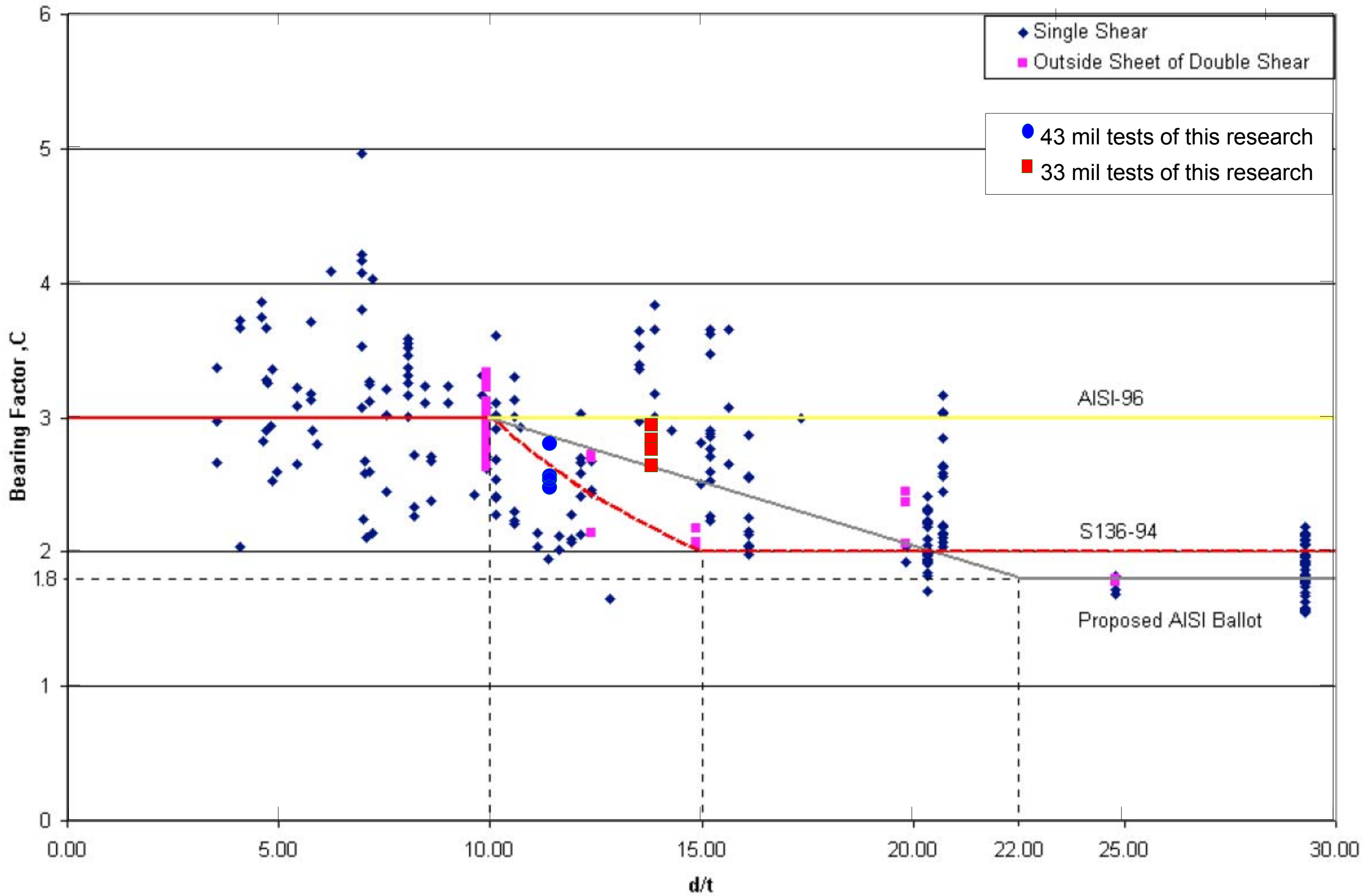


Fig 9-12 Bearing Factor C for Single Shear and Outside Sheets of Double Shear Bolted Connections [With Washers] (Wallace, LaBoube, Schuster, 2001)

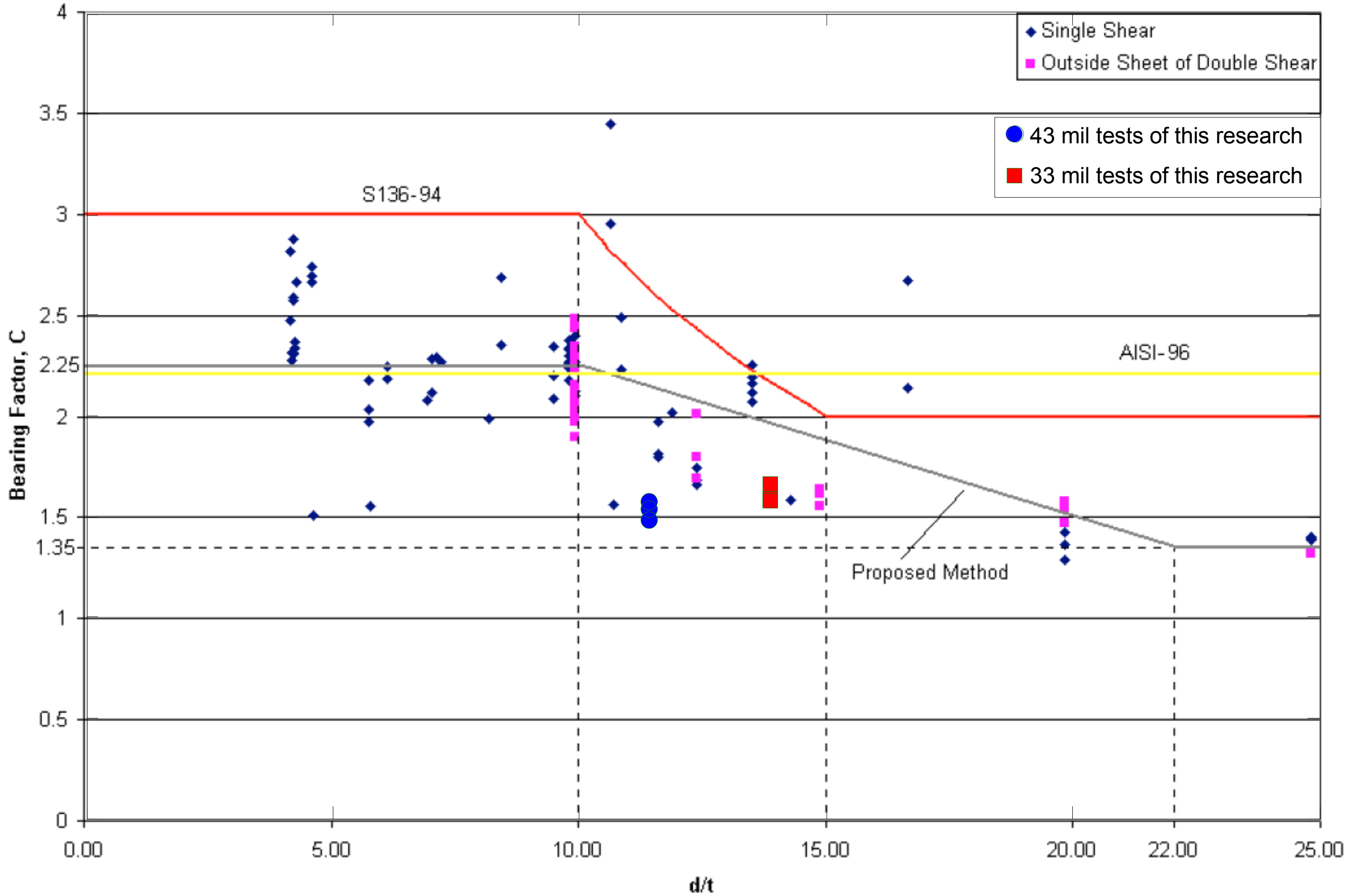


Fig 9-13 Bearing Factor C for Single Shear and Outside Sheets of Double Shear Bolted Connections [Without Washers] (Wallace, LaBoube, Schuster, 2001)

9.8 SHEET BEARING STRENGTH OF BOLTED CONNECTIONS WITHOUT WASHERS ON SLOTTED HOLES

The test results of connections with slotted holes were compared to the connections with oversized holes and the predictions by design methods including the current NAS (2007) method and the new design method proposed in Section 9.1 of this report. The test-to-predicted ratios "P_{test}/P_{NAS}" are listed in Tables 8-11 and 8-12 where P_{test} is the peak load per bolt and P_{NAS} is the NAS (2007) prediction for the bearing strength of single shear without washers for the thinner sheet.

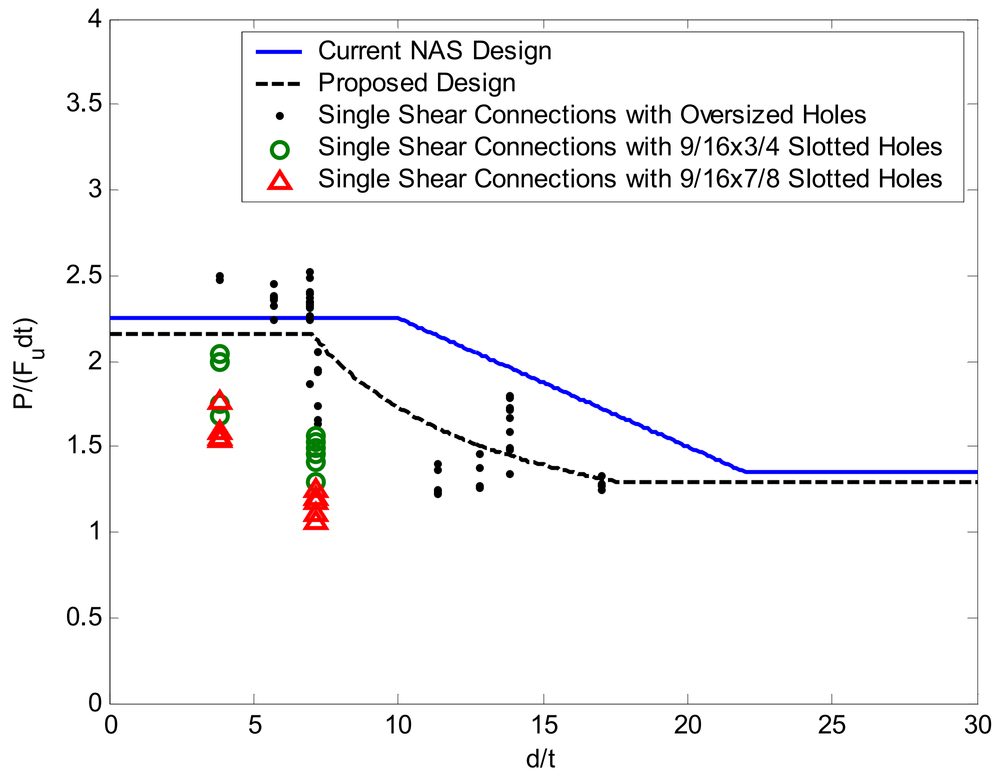


Fig 9-14 Test Results vs. Design Methods for Single Shear Connections in Bearing

Figure 9-14 illustrates a comparison in bearing strength between the test results with the design methods. It indicates that the single shear connections using two different slotted holes yield significantly lower bearing strength than the connections using oversized holes. The average test-to-NAS prediction ratio for the single shear connections with 9/16"×3/4" slots is 0.72. For the single shear connections with 9/16"×7/8" slots, the ratio is 0.60. The reduction in bearing strength is because the slotted holes are wider than the oversized holes thus make it easier for the bolt head and nut to rotate and go through the sheets. It is suggested that washers be required for single shear bolted connections with 9/16”×3/4” or 9/16”×7/8” slotted holes.

In the double shear tests the tilting of bolt was prevented, it resulted in increase in the bearing strength in double shear. Figure 9-15 illustrates the comparison between the test results and the design methods for the bearing strength of inside sheet of double shear connections. It indicates that the double shear connections with slotted holes have similar performance to the connections using oversized holes in terms of the bearing strength. The proposed design method for bearing strength has a reasonable match to the test results. The average test-to-prediction of the new design method for the double shear connections with 9/16”×3/4” slots is 0.99 with a standard deviation of 0.163. For the double shear connections with 9/16”×7/8” slots, the average ratio is 0.96 with a standard deviation of 0.149. It is recommended that the newly proposed design method (e.g. the Tables 9-2, 9-3) be applicable for the inside sheet of a double shear bolted connection with 9/16”×3/4” or 9/16”×7/8” slotted holes. The ratios of test-to-prediction of the new design method (P_{test}/P_{NEW}) are listed in Tables 8-13 and 8-14.

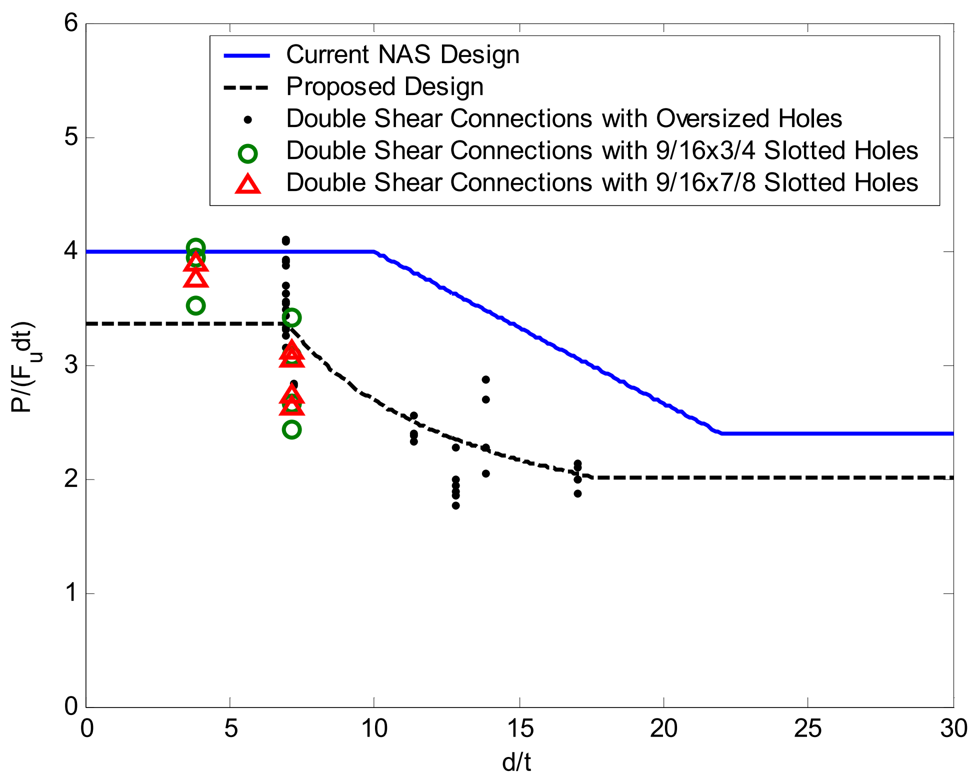


Fig 9-15 Test Results vs. Design Methods for Double Shear Connections in Bearing

9.9 SHEET SHEAR STRENGTH OF BOLTED CONNECTIONS WITHOUT WASHERS ON SLOTTED HOLES

The test results were compared with the NAS prediction for shear strength of bolted connections using standard holes. The test-to-NAS prediction ratios are listed in Tables 8-15 and 8-16. Due to the significant tilting of the bolt in the single shear connections with slotted holes, the tested shear strength is systemically lower than the NAS predictions, the average test-to-predicted ratio is 0.80 with a standard deviation of 0.114. In the double shear tests, the tilting of the bolt was prevented so that typical shear failure was achieved and the connection strength was greatly improved. The peak loads of the double shear tests had a good agreement with the NAS prediction, the average test-to-predicted ratio is 1.03 with a standard deviation of 0.037. Figure 9-16 shows the comparison between the test results and the NAS prediction. It is suggested that the current NAS prediction for sheet shear strength be applicable for double shear connections using 9/16” × 3/4" and 9/16” × 7/8" slotted holes. It is also recommended that washers be required for single shear connections with slotted holes in shear.

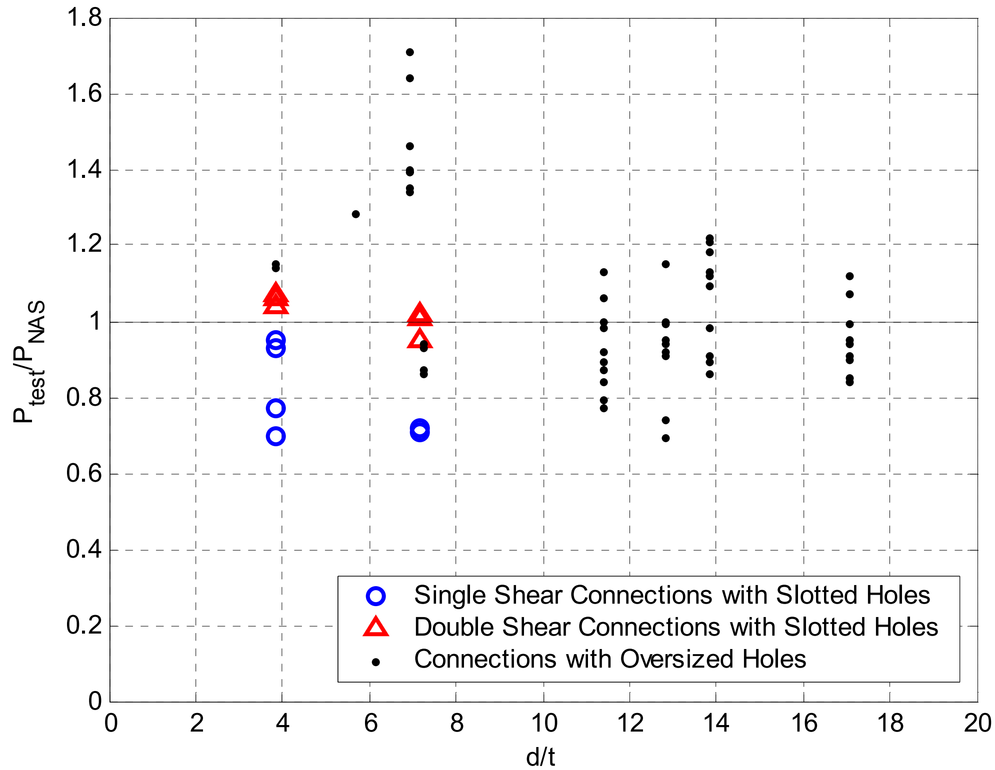


Fig 9-16 Test Results vs. Design Methods for Double Shear Connections in Shear

9.10 TWO-BOLT CONNECTIONS WITH SLOTTED HOLES IN BEARING AND SHEAR COMBINED FAILURE

The bearing and shear combined failure mode is expected to occur on the connections with two bolts and e/d = 1.5. The specific configuration was investigated on 68 mil connections and the results are summarized in Table 8-17. Table 9-13 presents a comparison between the combined failure with the other two typical failures. P_{test} in Table 9-13 is the average peak load per bolt. It shows that the strength of the combined failure is close to sheer failure. It is appropriate to predict the strength of the specific configuration by assuming both bolts fail in the sheet shear failure.

Table 9-13 Comparison between Combined Failure and Typical Failures for Single Shear Connections

Connection Configuration	P_{test} (lbs)		
	Combined Failure	Two Bolt Connections in Bearing	Single Bolt Connections in Shear
68 mil 9/16" × 3/4" slot	2484	4652	N/A
68 mil 9/16" × 7/8" slot	1976	3770	2035

10 PRELIMINARY CONCLUSIONS

The tensile tests on cold-formed steel connections without washers on oversized holes and slotted holes were conducted to investigate both the sheet shear strength and bearing strength. The results showed that current NAS (2007) design provisions for the sheet shear strength worked well for the bolted connections without washers on oversized holes in both single shear and double shear configurations. The NAS provisions also had a good agreement with the double shear connections without washers on slotted holes. The single shear connections without washers on slotted holes gave relatively low shear strength, therefore it is recommended that washers be required for single shear connections with slotted holes.

For the bearing strength, the test results showed that the bolted connections without washer on oversized holes and slotted holes gave lower strength than the connections with standard holes. Therefore the current NAS design method yielded unconservative predictions for those connections having greater holes. Based on the test results, new bearing factor and modification factor were proposed to account for the influence by the oversized holes. The new design method has a good agreement with to the tested bearing strength of connections without washers on oversized holes in both single shear and double shear. The method also works well for connections with slotted holes in double shear. Large reduction in bearing strength was found on the single shear connections with slotted holes, it is recommended that washers be required for those bolted connections.

It was also found that the low ductile steel can be treated equivalently as high ductile steel in terms of the design method for the bearing and shear strength of connections without washers on oversized holes. The test results indicated that connections using ASTM A325 bolts yielded higher bearing strength than connections using ASTM A307 Type A bolts because of the larger head and nut sizes in A325 bolts. This test program used ASTM A307 Type A bolts for the majority of the specimens, the proposed design method shall be applicable for connections using ASTM A325 bolts.

11 CONTINUING RESEARCH

The Phase 1 research on the bearing failure and shear failure in the sheets was completed. The research moves forwards to Phase 2 to study the fracture in the net section of the sheets

12 ACKNOWLEDGEMENT

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