COLD-FORMED STEEL BOLTED CONNECTIONS WITHOUT WASHERS ON OVERSIZED AND SLOTTED HOLES

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Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

May 2009

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Sheerah, Ibraheem. Cold-Formed Steel Bolted Connections without Washers on Oversized and Slotted Holes. Master of Science (Engineering Systems), May 2009, 104 pp., 37 tables, 66 figures, references, 31 titles.

The use of the cold-formed steel sheet bolted connections without washers is so significant; however, the North American Specifications for the Design of Cold Formed Steel Structural Members, NASPEC, doesn't provide provisions for such connections. The bearing failure of sheet and the shear failure of sheet were considered in this study. For the sheet shear strength, it was found that the NASPEC (2007) design provisions can be used for oversized holes in both single and double shear configurations and for the double shear connections on short slotted holes. For the sheet bearing strength, a new design method was proposed to be used for low and high ductile steel sheets. The method was compared with the NASPEC and the University of Waterloo approach. Washers were still required for single shear connections on short slotted holes. Besides, connections using ASTM A325 bolts yielded higher bearing strength than connections using ASTM A307 bolts.

ACKNOWLEDGEMENTS

I would like to thank God for giving me the strength to complete this research study. I am truly grateful to my thesis advisor, Dr. Cheng Yu for allowing me to be a member of his construction research team, for his expertise, kindness, excellent guidance, and most of all, for his patience. I would like also to express my appreciation to my advisory committee members, Dr. Seifollah Nasrazadani and Dr. Phillip R. Foster, and the department chair, Dr. Nourredine Boubekri, for their understanding, unlimited support and guidance throughout my graduate program. The funding provided by the AISI is gratefully acknowledged. The assistance and guidance provided by the AISI COS Oversized Hole Task Group is highly appreciated. A special thank goes to the Blue Scope Steel for providing us with low ductile steel sheets (ASTM A875 HSLAS Grad 80) and Simpson Strong - Tie for the 68 mil and 118 mil sheet specimens (ASTM A653 SS Grade 33). The assistance of the UNT undergraduates George Trabazo, Stephen Mathai, and Szu-Chun Hung in preparing the test specimens has been invaluable. I am greatly indebted to Dr. Khalid Biyari, VP of Telecom SYS and R&D, in the Advanced Electronics Company for supporting me to pursue a degree in mechanical engineering. Finally, I would like to thank my mother, whose love is boundless, my father who just passed away in April 2007, and my wife for supporting me in completing my degree.

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CHAPTER 1

INTRODUCTION

1.1. Overview of the Study

The use of cold-formed steel structures in the construction industry has grown rapidly. Durability, strength, material consistency, and ecological concerns are some of the reasons given for the increasing applications of cold-formed steel in the market. The bolted connections method is one important type of joining steel sheets in any structure. Many research projects in the past experimentally investigated bolted connections with and without washers for standard holes. Accordingly, remarkable results were achieved and used by designers. However, bolted connections using oversized and short slotted holes without washers have not been fully studied.

Preliminary experimental results show that failures, such as shearing 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 the cold-formed steel bolted connections. Figure (1.1) illustrates the first three types of failure modes.

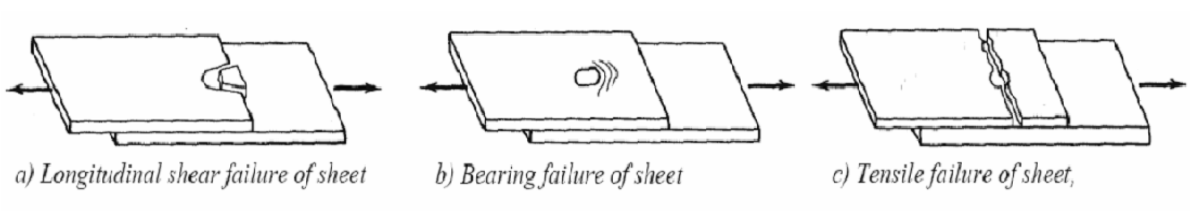


Figure 1.1 The first three types of failures of bolted connections.
(Zadanfarrokh & Bryan 1992)

The current North American Specification for the Design of Cold-Formed Steel Structural Members (NASPEC 2007) provides design provisions for those three types of failure respectively. The dimensions of the perforations, either holes or short slots, and the use of washers are listed in the NASPEC 2007 standard (Yu 1982). The dimensions of the hole together with the use of washers may significantly influence the first three types of failures. The NASPEC (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 investigated the two failure modes of the cold-formed steel bolted connections without washers for oversized and short slotted holes.

The experimental study examined the shear and the bearing failures of the sheets. The test matrices were 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 and ASTM 325; (5) the material ductility in sheets - low and high; (6) the diameter of the bolt – 1/4 in. and 1/2 in.

Eventually, the test results are to be compared with those of other studies and with the current NASPEC design provisions for connections with non-washer and standard holes. New design provision was developed to account for the combined effect of non-washer and oversized/short slotted hole to the strength of the cold-formed steel bolted connections.

1.2. Motivation

The cold-formed steel sheet bolted connections in oversized and short slotted holes without washers have not been fully studied yet. The current NASPEC specifications do not include provisions for such configurations. Nevertheless, those types of connections may significantly improve the construction efficiency if the desired strength can be achieved. This research intensively investigated the behavior and strength of bolted connections without washers on oversized holes and short slots. These types of connections configurations are still under development and need further studies. Not much work has been done regarding the structural performance of bolted connections between cold-formed steel sheets of single and double shear, without washer, on oversized and short slotted holes.

Most studies on the cold-formed steel sheet bolted connections considered only the configurations with standard holes. Testing and analysis of the cold-formed steel sheet bolted connections of single and double shear, without washer, on oversized and short slotted holes is an important and rich subject in the construction business.

1.3. Literature Review

The use of cold formed sections in structures has been rapidly growing. The emphasis on the heavy use of cold-formed steel in the market is due to its durability, strength, material consistency, and ecological concerns. There is a necessity of reliable design provisions that improve and support the use of cold formed steel over different types of constructions in the market.

In construction, connections are an important aspect due to the fact that structural behavior is determined to some extent by the performance of the connections (Zadanfarrokh & Bryan 1992). There are many types of fastenings between structural members. In cold formed steel sections, the bolted connection is one of the most common connections used in practice (Zadanfarrokh & Bryan 1992). Studying the behavior of bolted connections for standard holes with washers between cold-formed steel sections is crucial in order to simulate the real behavior of bolted joints and facilitate the cold-formed steel structures to be economically considered in design (Zadanfarrokh & Bryan 1992).

In the 1940s, four major types of failure were observed by George Winter and later by a number of researchers. These four types of failures have formed the basis for the current provision of design equations in different codes of practice (Zadanfarrokh & Bryan 1992, Winter, G. 1956). The researchers had observed distinct types of failures. The first type of failure they identified was type I, the Longitudinal Shear Failure of Sheet, which occurred for short edge distances and along two parallel planes (Winter, G. 1956). The second type of failure, type II, the bearing failure of sheet, occurred for long edge distance and along two different inclined planes with observable “pilling-up” of the sheet in front of the bolt (Winter, G. 1956). The third failure, type III, the tensile failure in net section of sheets, occurred when strength of the bolted connection is greater than the ultimate strength of the net section (Zadanfarrokh & Bryan 1992, Winter, G. 1956). The last mode of failure, type IV, the shear failure of bolt, occurred when the bearing strength of the joined sheets exceeds the shear strength of the bolt (Zadanfarrokh & Bryan 1992, Winter, G. 1956).

However, previous researchers indicate a number of specimens failed in a combined mode. When investigating the behavior of bolted connection for standard holes with washers, and sheets subjected to tension, the tension force was conveyed through the bolts until a slip load was reached. The tension force was carried by bearing, in addition; friction and failure was either separate mode or combined mode.

Eventually, not all failures were of these clearly different types (Winter, G. 1956). For likely small end distances, 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, in the direction of the applied load, the connection may fail by longitudinal shearing of the sheet (Zadanfarrokh & Bryan 1992, Winter, G. 1956). It was found that this mode of failure depended on the thinnest sheet thickness (t), the tensile strength of connected sheet (F_u), and the end distance (e). The nominal shear strength per bolt (P_n) can be expressed as Equation 1.1 (NASPEC. 2007).

$$P_n = t\ e\ F_u \tag{1.1}$$

In other words, 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 (Winter, G. 1956). On the other hand, for adequately large end distances, the connection may fail by the bearing failure. The influence of the presence of washers to the strength of Type I failure can be ignored in design (NASPEC 2007).

When the edge distance in the bolted connections is considerably large (e/d > 2.5), the bearing failure, the pilling up of steel sheet in front of the bolt, 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. Bearing connections could be either single or double shear, with or without washers (Zadanfarrokh & Bryan 1992, LaBoube & Yu 1995, Wallace & Schuster 2002). The presence of washers has significant impact on the bearing strength. It was also found that, for standard holes, the maximum bearing stress at failure for bolts with washers was about 45% more than those without washers (Winter, G. 1956). The current North American Specifications consider the use of washers by using a modification factor (m_f) in the equation. The nominal bearing strength, therefore, is expressed as Equation 1.2 (NASPEC 2007).

$$P_n = m_f\, c\, d\, t\, Fu \tag{1.2}$$

Where:

c = bearing factor

d = nominal bolt diameter

t = uncoated sheet thickness

F_u = tensile strength of sheet

m_f = modification factor (0.75 for single shear and 1.33 for double shear)

Having high torque values did not affect the ultimate strength of the connection. Nevertheless, the slip load values were, in general, increased with higher torques (Winter, G. 1956).

One should note that the bearing equation in NASPEC (2007) is only applicable to the connections with standard holes.

The research done by Zadanfarrokh and Bryan in 1992 had investigated the shearing failure of sheets and bearing failure of sheets. They had chosen two thicknesses, 0.067 in. and 0.118 in. and they had used galvanized grade 4.6, 8.8 and 10.90 bolts of 5/8" diameter. The torque that was applied was from 44 to 74 ft. lb. The research shows that the strength of the connection between cold-formed steel sheets may dictate the strength of the sheets or the assembly. Also, it was found the complete rigidity was difficult to acquire through the connection (Zadanfarrokh & Bryan 1992).

For the shear test, researchers had found that the allowable tension stress for the net section of connected sheets is established by the tensile strength of the connected part, F_u, and the is based on configuration of the connection, if it is a single shear lap joint or a double shear joint (Yu, W. W. 1982). Regarding the influence of bolts, the research that was done by Yu, W. W. in 1982 indicates that, by using A325 grade bolts, the allowable shear stress was increased by 36% in the 1980 design provisions (Yu, W. W. 1982).

Some research used a range of cold-formed steel gages range from 20Ga to 8Ga and bolts ranged from 1/4 in. to 1 in. All bolt holes were punched, according to a number research, oversize. A research used 1/32 in. for 1/4 in. and 3/8 in. bolts and 1/16 in. for bolts greater than 3/8 in. (Winter, G. 1956a). However, the NASPEC specifications have different values for the oversized holes and standard holes. For instance, for 3/8 in. bolts, 13/32 in. is the standard diameter of the hole and 7/16 in. is diameter of an oversize hole. As for the material used, a study had used normal strength steels with yield strength ranges from 26ksi to 36.6ksi and high strength steel with yield strength ranges from 46.75ksi to 56.5ksi (Winter, G. 1956a). On the other hand, the research used different torque values for different bolts, such as 5 ft. lb for 1/4 in. bolt diameter, 14 ft. lb for 3/8 in. bolt diameter and 40 ft. lb for 1/2 in. bolt diameter. The study, also, recognized single shear and double shear configurations, double and single bolt (Winter, G. 1956a). It was shown that Type II failure, sheet shear failure, accompanied by remarkable “pilling up” of material in the front of the bolt takes place at a bearing stress equal to “4.8 times the yield strength of the sheet.” (Winter, G. 1956a). From the other hand, Type II failure most likely occurs when the nominal shearing stress is 70% greater than the sheet yield stress (Winter, G. 1956a).

Because of the small thicknesses of material in cold-formed steel bolted connections, the strength of the connections may often determine the strength an assembly (Zadanfarrokh & Bryan 1992). In addition, in such connections complete rigidity is difficult to obtain. Researchers, therefore, emphasize on joint flexibility (Zadanfarrokh & Bryan 1992).

Another study by Wallace and Schuster on 2002 was concerned with such a configuration where washers may not be used. It was shown that for single shear – single standard bolt connection with washers the average tested bearing stress to the nominal bearing stress (P_t/P_c), by using the S136 (NASPEC 2007) approach, was 1.030, for double shear – single standard bolt with washers configuration P_t/P_c = 0.986, and for double shear – double standard bolt with washers configuration P_t/P_c = 0.997. Whereas for single shear – single standard bolt connection without washers the average tested bearing stress to the nominal bearing stress (P_t/P_c), by using the S136 approach, was 0.750, for double shear – single standard bolt without washers configuration P_t/P_c = 0.723, and for double shear – double standard bolt with washers configuration P_t/P_c = 0.782 (Wallace, J. A,, Schuster, R. M. 2002).

On the other hand, It was shown that for single shear – single standard bolt connection with washers P_t/P_c, by using the AISI Method for Bolted Connections in Bearing, was 0.911, for double shear – single standard bolt with washers configuration P_t/P_c = 0.864, and for double shear – double standard bolt with washers configuration P_t/P_c = 0.997. Whereas for single shear – single standard bolt connection without washers the average tested bearing stress to the nominal bearing stress (P_t/P_c), by using the AISI method for bolted connections in bearing, was 0.893, for double shear – single standard bolt without washers configuration P_t/P_c = 0.857, and for double shear – double standard bolt with washers configuration P_t/P_c = 1.057 (Wallace, J. A,, Schuster, R. M. 2002).

Finally, the proposed AISI and S136 methods for bolted connections in bearing with washers, presented in Wallace and Schuster study, show good results. For example, for double shear – single standard bolt with washers configuration P_t/P_c = 0.962 compared to 0.864 by AISI approach and 0.986 by S136 approach (Wallace, J. A,, Schuster, R. M. 2002).

The University of Waterloo method was utilized by Wallace and Schuster in their study (Wallace, J. A,, Schuster, R. M. 2002). It was shown that for single shear – single standard bolt connection with washers P_t/P_c, by using the Waterloo Method, was 1.024, for double shear – single standard bolt with washers configuration P_t/P_c = 0.962, and for double shear – double standard bolt with washers configuration P_t/P_c = 0.997. Whereas for single shear – single standard bolt connection without washers the average tested bearing stress to the nominal bearing stress (P_t/P_c), by using the Waterloo Method, was 1.031, for double shear – single standard bolt without washers configuration P_t/P_c = 0.985, and for double shear – double standard bolt with washers configuration P_t/P_c = 1.043 (Wallace, J. A,, Schuster, R. M. 2002).

Wallace and Schuster had proven that that when studying the sheet bearing failure, using standard holes, the use of washers is significant in bolted connection. All the AISI method, the S136 method and the Waterloo method are encompassed by the current NASPEC specifications.

When looking to the comparison between the AISI method, the S136 method and the proposed AISI method, Wallace and Schuster found that, for standard hole with washers -Single Shear and Outside Sheets of Double Shear Connection, the average AISI-96- P_t/P_c = 0.879, and the average S136-94 P_t/P_c = 1.076 whereas the average proposed AISI P_t/P_c = 1.052. For standard hole without washers -Single Shear and Outside Sheets of Double Shear Connection, the average AISI-96- P_t/P_c = 0.965, and the average S136-94 P_t/P_c = 0.783 whereas the average proposed AISI P_t/P_c = 1.012. Finally, for standard hole with or without washers -Inside Sheets of Double Shear Connection, the average AISI-96- P_t/P_c = 1.283, and the average S136-94 P_t/P_c = 1.396 whereas the average proposed AISI P_t/P_c = 1.001 (Wallace, J. A,, Schuster, R. M., LaBoube, R. A. 2001).

The AISI method for bolted connections in bearing with washers, based on the work by Rogers and Hancock in 2000, gave good statistical results. The method that was proposed by Wallace, Schuster and LaBoube in 2001 for single shear and outside sheets of double shear bolted connections failing in bearing without washers resulted in better statistical predictions in comparison to the current AISI and S136 design methods.

It had been shown that the method was also true for the inside sheet of a double shear bolted connection failing in bearing, with or without washers. For single shear and outside sheets of double shear bolted connections with washers the bearing factor, C, values could be calculated as shown on Table 2.1 in Chapter 2.

According to the study, for single shear and outside sheets of double shear bolted connections without washers the bearing factor values in Table 1.1 are to be multiplied by 0.75, whereas for inside sheets of double shear bolted connections with or without washers the values in table 1.1 are to be multiplied by 1.33. The key factors that were investigated are the bearing factor C and the modification factor m_f. These two factors together with the ration of the nominal bolt diameter to the actual sheet thickness d/t play significant role in measuring the bearing strength and shear strength of the connected sheets. The value of the modification factor m_f helps distinguishing between the single shear the double shear (NASPEC, 2007).

It was observed that the plates were in firm contact but were slip under loading until the hole surface bears against the bolt. The load transmitted from plate to bolt is therefore by bearing and the bolt is in shear.

The use of short slotted holes in the cold formed steel bolted connection was not fully covered by the previous research. Short slotted holes could be utilized in bearing type connection; however, for better results, short slotted holes should have their length normal to the direction of the load in bearing type connections (NASPEC 2007). Figureure 1.2 shows the different type of holes; the oversized holes, the short-slotted holes, and the long-slotted holes. Table 1.1 gives the required dimensions of each of these holes (NASPEC 2007).

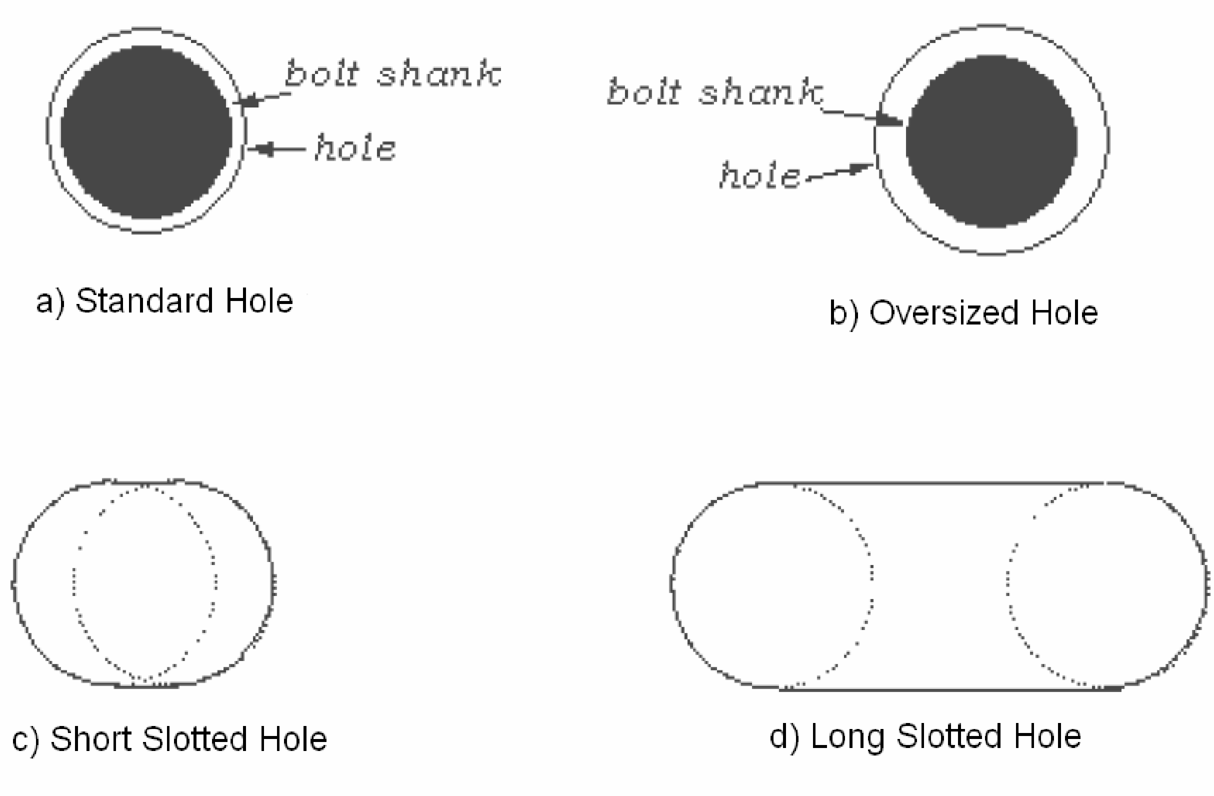


Figure 1.2 The four types of holes.

Table 1.1 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

Table 1.2 summarizes the previous tests that were conducted by a number of researchers from 1956 to 2002.

Table 1.2 Previous Studies

Research	Dimensions and Thickness of the Sheets	Bolt Type and Diameter and Hole Size	Steel Type, Washers, and Configuration	Number of Tests	Results
LaBoube, R. A 1995	0.04", 0.07", 0.120" 15.75" x 2.95" and 17.23" x 3.74"	Bolt type A325T 0.5" and hole size was 9/16"	Fu/Fy = 1.56 for 0.04", Fu/Fy = 1.64 for 0.07" and Fu/Fy = 1.45 for 0.120" with washers and the majority without washers Single Shear, Single bolt	35 tests	Mean Bearing factor c = 1.93, Pt/Pc ranges from 0.774 to 1.284 with a mean of 1.001
Rogers, C.A., Hancock, G.J., 1999	0.0315" and 0.0394" 15.75" x 2.95" and 17.23" x 3.74"	Bolt dia. Was 0.472" and hole diameter 0.563"	G550 Fu/Fy = 1.04 for 0.0393" thick G550 Fu/Fy = 1.00 for 0.0315" thick G300 Fu/Fy = 1.15 for 0.0315" thick with washers Single Bolt and Double bolt	228 tests	**AS/NZS 4600 (1996) & AISI (1997a)** Pt/Pc = 0.880, number of tests = 176 **CSA-S136 (1994)** Pt/Pc = 1.115, number of tests = 176 **Eurocode 3 (1996)** Pt/Pc = 0.959, number of tests = 176 **Proposed Method** Pt/Pc = 1.077, number of tests 176
Zadanfarrokh, F., Bryan, E. R. 1992	0.067" to 0.118" 15" x 4"	Bolt is 0.63" diameter 0.63" hole diameter and 0.63"+0.079" diameter holes	Fu/Fy = 1.29 CFS Fu/Fy = 1.39 CFS With and without washers Single Shear	704 number of tests with 176 per test method	The strength for connection with washers was 100% The strength for connections without washers was 70% Slip load between 674 lb. f to 2248 lb. ft
Wallace, J. A,, Schuster, R. M. and LaBoube, R. A. 2002	0.0252 in., 0.0543 in. Sheet width was 2"	A307 3/8", 5/16", 5/8", 1/2", 1/4" 0.563" for 1/2" bolts 0.437" for 3/8" bolts 0.375" for 5/16" bolts 0.313" for 1/4" bolts 0.689" for 5/8" bolts	Fu/Fy = 1.09 for 0.0252" Fu/Fy= 1.01 for 0.0543" With and without washers Single Shear Double Shear	60 tests AISI method , with washers 59 tests AISI method, without washers 60 tests CSA 1994 , with washers 59 tests CSA 1994 method, without washers	**By using AISI 1996 method,with washers** 21 tests, single shear, single bolt, Pt/Pc = 0.911 30 tests, double shear, single bolt, Pt/Pc = 0.864 9 tests, Double Shear, Double Bolt, Pt/Pc = 0.997 **By using AISI 1996 method,without washers** 20 tests, single shear, single bolt, Pt/Pc = 0.893 30 tests, double shear, single bolt, Pt/Pc = 0.857 9 tests, Double Shear, Double Bolt, Pt/Pc = 1.057 **By using S136 method,with washers** 21 tests, single shear, single bolt, Pt/Pc = 1.030 30 tests, double shear, single bolt, Pt/Pc = 0.986 9 tests, Double Shear, Double Bolt, Pt/Pc = 1.003 **By using S136 method,without washers** 20 tests, single shear, single bolt, Pt/Pc = 0.750 30 tests, double shear, single bolt, Pt/Pc = 0.723 9 tests, Double Shear, Double Bolt, Pt/Pc = 0.782

(table continues)

Table 1.2 (continued)

Research	Dimensions and Thickness of the Sheets	Bolt Type and Diameter and Hole Size	Steel Type, Washers, and Configuration	Number of Tests	Results
LaBoube, R. A., Yu, W. W. 1996	0.04 in., 0.07 in., 0.12 in.	A325 1/2" the bolt diameter hole is defined as 1/16 in. greater than nominal hole diameter (standard hole 9/16")	Fu/Fy =1.56 for 0.04" thick Fu/Fy =1.64 for 0.07" Fu/Fy=1.45 for 0.12" With and without washers Single shear Double Shear	229 tests, single shear 489 tests, double shear	P_t/P_a ranges from 0.808 to 0.949, a mean of 0.8
Gilchrist, R.T., Chong, K. P. 1979	22, 24 & 26Ga 15" x 4"	A307 1/4", 3/8" &1/2" (9/32" for bolt dia 1/4") (13/32" for bolt dia 3/8") (9/16" for bolt dia 1/2")	Painted Galvanized Without Washers Single Shear	6 tests 26Ga 6 tests 24Ga 18 tests 22Ga	For Galvanized steel (26,24,22Ga), ranges from 82 KSI to 151 KSI For Painted steel (22Ga), ranges from 82 KSI to 144 KSI
Winter, G. 1956	From 20Ga to 8Ga 16" x 5"	A307 and A325 1/4", 3/8", 1/2" & 1" Hole Size: (+1/32" for bolt dia. 1/4" and 3/8") (+1/16" for bolt dia. 1/2" and 1")	Painted Galvanized With Washers Single Shear Double Shear	56 tests with 8Ga 84 tests with 10GA 96 tests with 12GA	For double Shear, Single bolt, Painted steel, max load about 12500 pounds For single Shear, Single bolt, Painted steel, max load about 10000 pounds For double Shear, Single bolt, galvanized steel, max load about 14000 pounds For single Shear, Single bolt, galvanized steel, max load about 13000 pounds

1.4. Objectives

The main research objectives of this thesis were 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, and II failures of the specific bolted connections were addressed in this study

The objectives include:

- 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 NASPEC Section E3.1 with the test results.
- Study the bearing failure, Type II failure, of the connected sheets without considering the deformation of the hole, and examine the applicability of NASPEC Section E3.3.1 with the test results.
- 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 NASPEC Section E3.3.2 to bolted connections without washers on the oversized and short slotted holes.
- Study the performance of the two grades of bolts, ASTM A307 Grade A and ASTM A325 Type 1, throughout Type I and II failures.
- Study the behavior of the low ductility and high ductility steel in the connections.

CHAPTER 2

DESIGN METHODOLOGY

2.1. Bearing Strength Methods

The current NASPEC (2007) specification does not provide provisions for cold-formed steel bolted connections in oversized or short slotted holes without washers. However, the use of washers with standard holes has been well studied by a number of researchers (Yu 1982, Zadanfarrokh & Bryan 1992, LaBoube & Yu 1995, Wallace & Schuster 2002). The current design method for bearing strength in NASPEC (2007) was based on the research done by Wallace, Schuster, and LaBoube 2002 in which the Waterloo method and current NASPEC methods were developed.

2.2. Waterloo Method

The Waterloo method for cold-formed steel bolted connections without washers on standard holes is expressed in Equation 2.1. 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.

$$P_n = C\ d\ t\ Fu \qquad (2.1)$$

Where

P_n = nominal bearing strength per bolt (lb)

C = bearing factor, value from Table 1

d = nominal bolt diameter (inches)

t = uncoated sheet thickness (inches)

Fu = tensile strength of sheet (ksi)

Table 2.1 Factor C, for Bearing Resistance 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

2.3. Current NASPEC Method

The current NASPEC (2007) method for bearing of bolted connections with standard holes is presented in Chapter 1, Equation 1.2. Unlike the Waterloo method, the NASPEC method is uses a linear function for the bearing factor, C. Furthermore the NASPEC utilizes a modification factor to account for the use of washers and the connection type. For single shear connections without washers 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. The bearing factor, C, for bolted connections is shown on table

Table 2.2 Bearing Factor, C, for Single Shear and Outside Sheets of Double Shear Bolted Connection With Washers (Wallace, J. A,, Schuster, R. M., LaBoube, R. A. 2001).

Ratio of fastener diameter to member thickness, d/t	C
d/t < 10	3.0
10 ≤ d/t ≤ 22	4 – 0.1(d/t)
d/t > 22	1.80

CHAPTER 3

EXPERIMENTAL EFFORTS

3.1. Testing Setup, Method and Assumptions

The tensile tests were conducted in a 20 kip universal testing machine, INSTRON, in a displacement control mode. The deformation of the bolted connection was measured by an extensometer with a gauge length of 0.9843 in. Figure 3.1 shows the test setup.

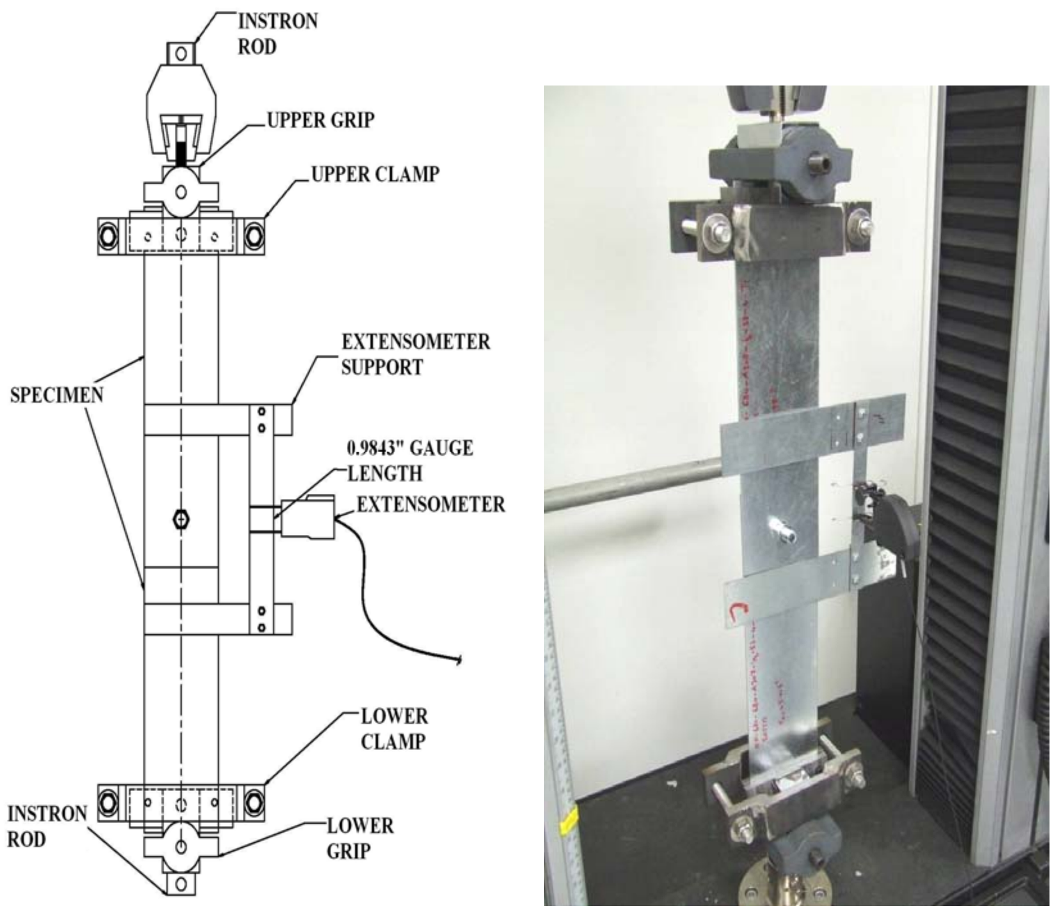


Figure 3.1 Setup for testing bolted connections.

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 0.1 in. per minute.

The applied force, the displacement of the top grip, and the deformation of the connection were measured and recorded simultaneously. All bolts were installed and tightened manually. A torque wrench was used to assure the applied torque not to exceed 40 lb-in.

Figure 3.2 Bottom fixture and top fixture.

The two grips, the top and the bottom grips shown in Figurer 3.2 were made specifically to hold the specimens. These grips could 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 in. outer diameter, 0.57 in. inner diameter and 0.093 in. thickness. The ASTM A307 Bolt and A325 shank diameters are the same 0.493 in. The head diameter for an A307 bolt is 0.739 in. and the head diameter for an A325 bolt is 0.862 in. The LVDT instrument was assembled as shown in Figurer 3.1 and the gauge length is 0.9843 in. The assumptions during the tests were that : (1) the surrounding humidity and temperature were always the same, (2) all bolts were installed in the center of the holes and full engagement was not achieved, and (3) the applied torque was always the same.

3.2. Preparing Sheets for Testing

On the preparation phase, AutoCAD was used to do engineering drawings for all sheets. The number of drawings was 21. Table 3.1 shows the labels of the sheets drawings. One sample drawing is shown on Figurer 3.3.

Table 3.1 Drawings Labels

		Number of sheets per thicknesses					
	Drawings Labels	0.1305" 118mil	0.0691" 68mil	0.0439" 43mil	0.0361" 33mil	0.0390" 39mil	0.0293" 30mil
A	5/8-1-OH-4	20	28	20	23	13	13
L	5/8-1-OH-1.5	8	26	15	13	13	13
T	5/16-1-OH-4	---	---	5	13	---	---
U	5/16-1-OH-1.5	---	---	5	13	---	---
B	5/8-2-OH-4	20	15	28	20	5	13
C	5/8-2-OH-1.5	8	13	20	13	5	13
V	5/16-2-OH-4	---	---	---	13	---	---
Y	5/16-2-OH-1.5	---	---	---	13	---	---
W	9/16-1-SH-4	---	3	---	3	---	---
X	9/16-1-SH-1.5	---	3	---	3	---	---
D	9/16-3/4-1-SS-4	18	20	---	---	---	---
F	9/16-3/4-1-SS-1.5	13	18	---	---	---	---
H	9/16-3/4-2-SS-4	18	15	---	---	---	---
J	9/16-3/4-2-SS-1.5	8	13	---	---	---	---
E	9/16-7/8-1-SS-4	18	20	---	---	---	---
G	9/16-7/8-1-SS-1.5	13	18	---	---	---	---
I	9/16-7/8-2-SS-4	18	15	---	---	---	---
K	9/16-7/8-2-SS-1.5	8	13	---	---	---	---
O	3/4-1-OH-4	13	---	---	---	---	---
P	3/4-1-OH-1.5	5	---	---	---	---	---
S	3/4-2-OH-4	13	---	---	---	---	---
TOTAL NUMBER OF SHEETS		201	220	93	127	36	52

Accordingly, a bill of materials (BOM) was formed for the whole study.

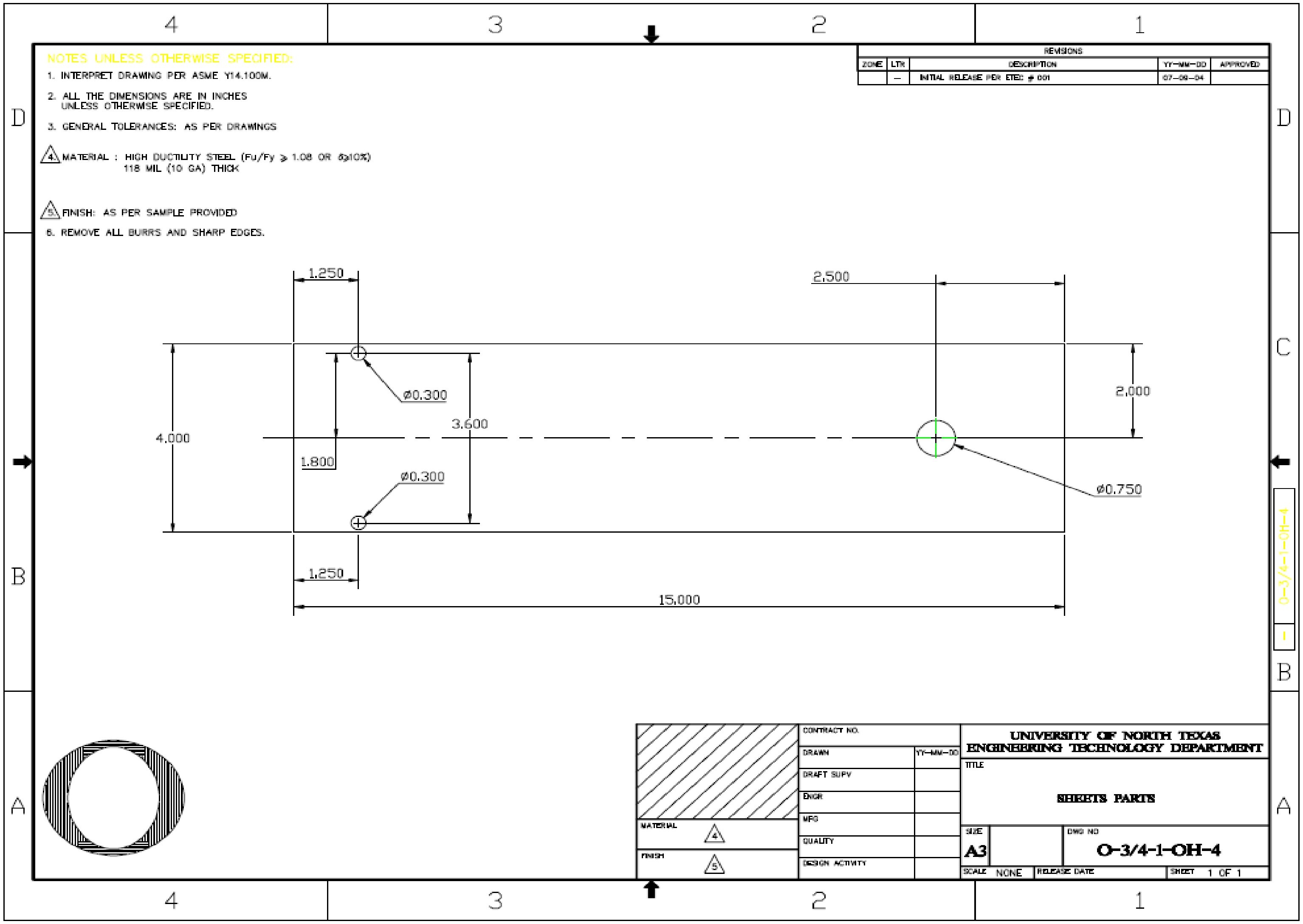
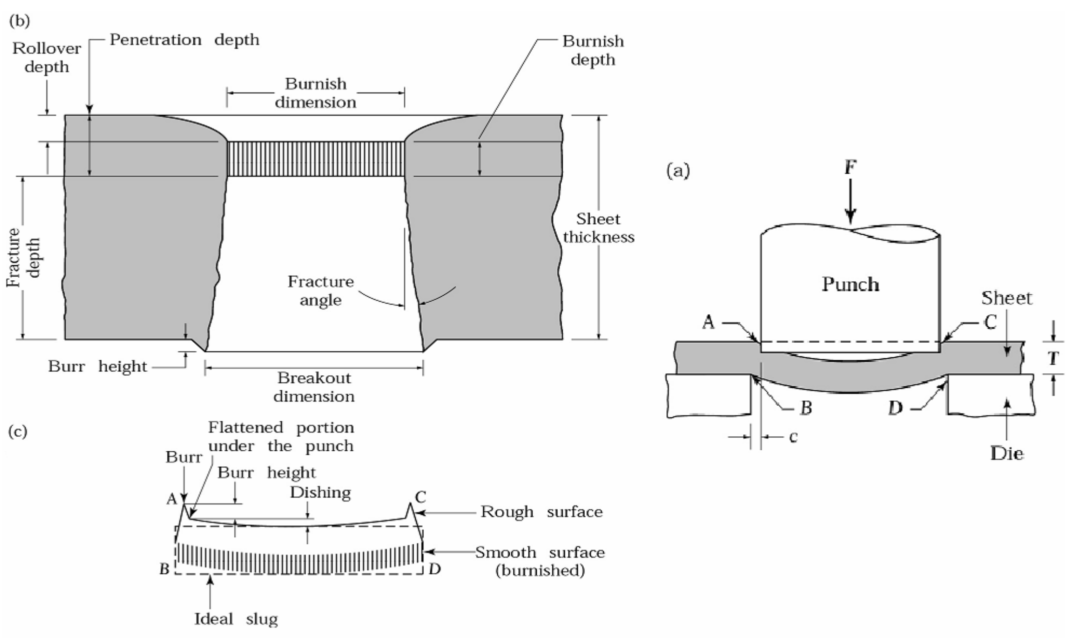


Figure 3.3 Sample drawings.

3.3. Punching Sheets

Punching was the method that was utilized on the previous researches. Therefore, 43 mil, 33 mil, 39 mil, and 30 mil sheets were punched manually by using KR Wilson 3 ton arbor press, a Lever-operated punch. The shearing process could be described as when shearing sheet metals, a blank which is a properly sized piece of sheet metal removed from a much larger sheet or coil by shearing. Shearing helps cutting sheet metals by subjecting a workpiece to shear stresses. Shearing starts with small cracks at points A, B, C, D, as shown on Figure 3.4, which eventually grow and meet. Rough fracture surfaces and smooth burnished surfaces result. Shear angles or beveled edges often used on shearing dies. Figure 3.4 shows: (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables, characteristic features of (b) a punched hole and (c) the slug.



Figurer 3.4 Punching sheet metal.

3.4. Coupon Tests

Coupon tests were carried out by the INSTRON universal testing machine to obtain material properties of the connected sheets following ASTM A370 Specification (ASTM 2007). Any coating on the cold-formed steel specimens was removed prior to the coupon tests by dipping them in dilute (10-20 percent) hydrochloric acid. 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 in. For each material thickness from the same coil, three coupons were cut and tested. The thickness of each material was measured from three points after removing coating, and the average values were reported and used in the analysis.

3.5. Test Specimens

Cold-formed steel sheet thicknesses range from 30 mil to118 mil. Single shear and double shear connections with one bolt or two bolts. ASTM A307 bolts (0.5 in. and 0.25 in. bolt diameters) and A325 bolts 0.5 in. bolt diameters were used on all proposed configurations of connections. The dimensions of oversize and short slotted holes refer to the maximum sizes specified in Table1.1. Besides the NASPEC specified short-slotted hole, MBMA slotted hole was also included in this research for 0.5 in. diameter bolts. 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.

The research focused on the tensile strengths of 45 ksi and 65 ksi in the steel sheets. The choice of tensile strength for each thickness of steel was subject to the product availability. High ductility steel (33mil, 43mil, 68mil, and 118mil) was used for most of the connection configurations. Low ductility steel (39mil and 30mil) was used for representative connections.

Shear failure and bearing failure in the connected sheets (Type I and II failures) were the primary concerns in that phase, therefore, the dimensions of specimens and test matrices need to be carefully designed to ensure the desired failure mode would occur.

Since this research focused 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 = 6.25d for bearing tests with the nominal bolt diameter d ≥ 0.4 in. Figure 3.5 shows the dimensions recommended by Zadanfarrokh and Bryan. Therefore the width of the sheets was set to 4 in.

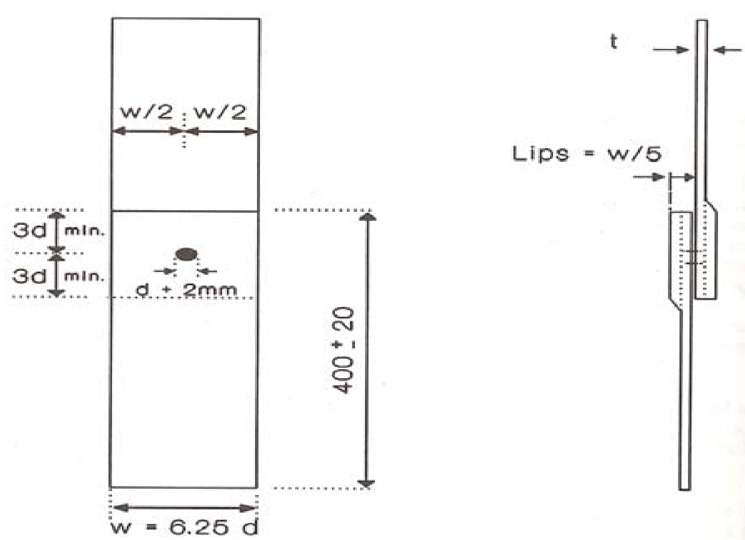


Figure 3.5 - Recommended test dimensions for structural bolts.
(Zadanfarrokh and Bryan, 1992)

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 an e/d=2.5 is approximately the transition point to distinguish between those two types of failures. Furthermore the NASPEC (2007) requires a minimum e/d = 1.5 for cold-formed steel bolted connections. Therefore, e/d values were selected to be 3, 4, and 8 for bearing failure and 1.5 for shear failure.

The length of the specimens, from edge to edge, was set to 15 in. which is based on the recommended value in Figure 3.5.

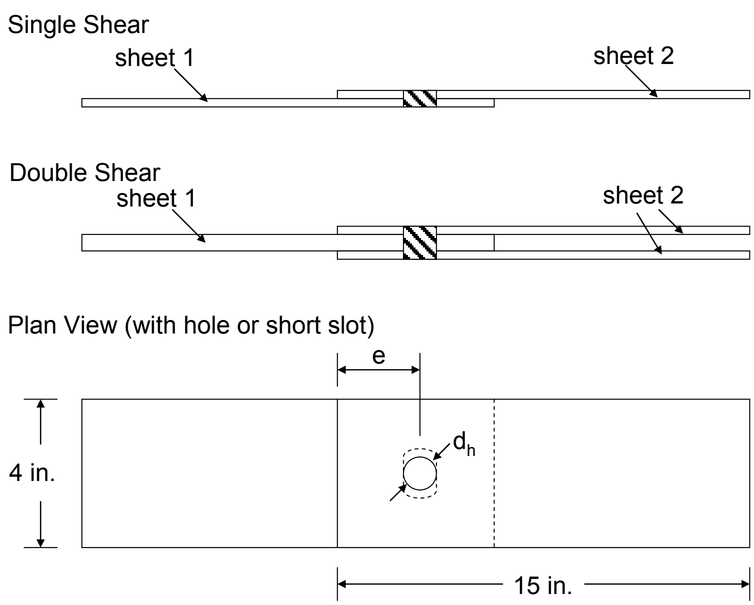


Figure 3.6- Dimensions of specimens with one bolt.

The sheet dimensions are shown in Figure 3.6 for one-bolt connections and in Figure 3.7 for two bolt connections. The distance between centers of the 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 NASPEC (2007).

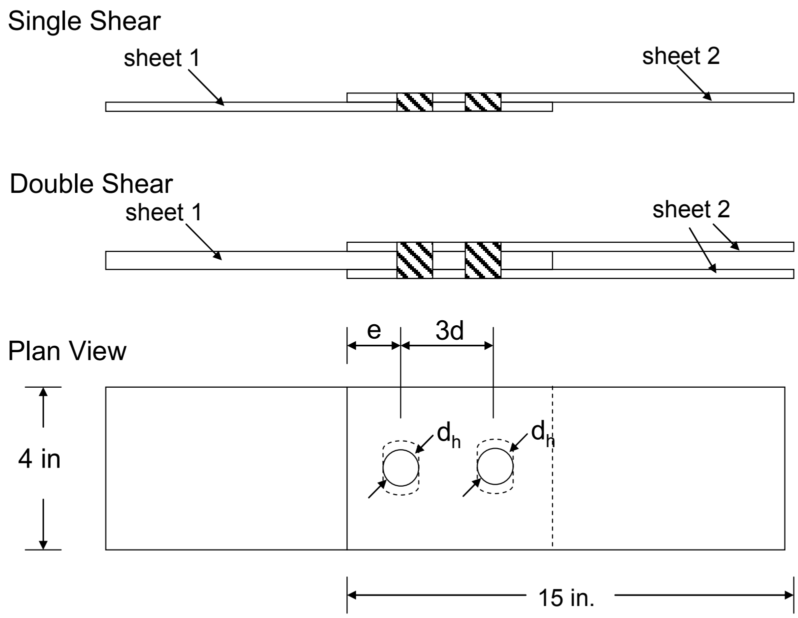


Figure 3.7-Dimensions of specimens with two bolts.

3.6. Specimens Labeling

The specimens were labeled during the preparation stage. A marker was used to write the labels on each specimen. Actual measurements were taken and recorded on each sheet. The measurements include, the actual edge distance e_A, the actual hole diameter d_H, and in case of double bolts, the distance between the two centers of the holes was measured and recorded on sheet. Figure 3.8 shows a sample sheet with written information.

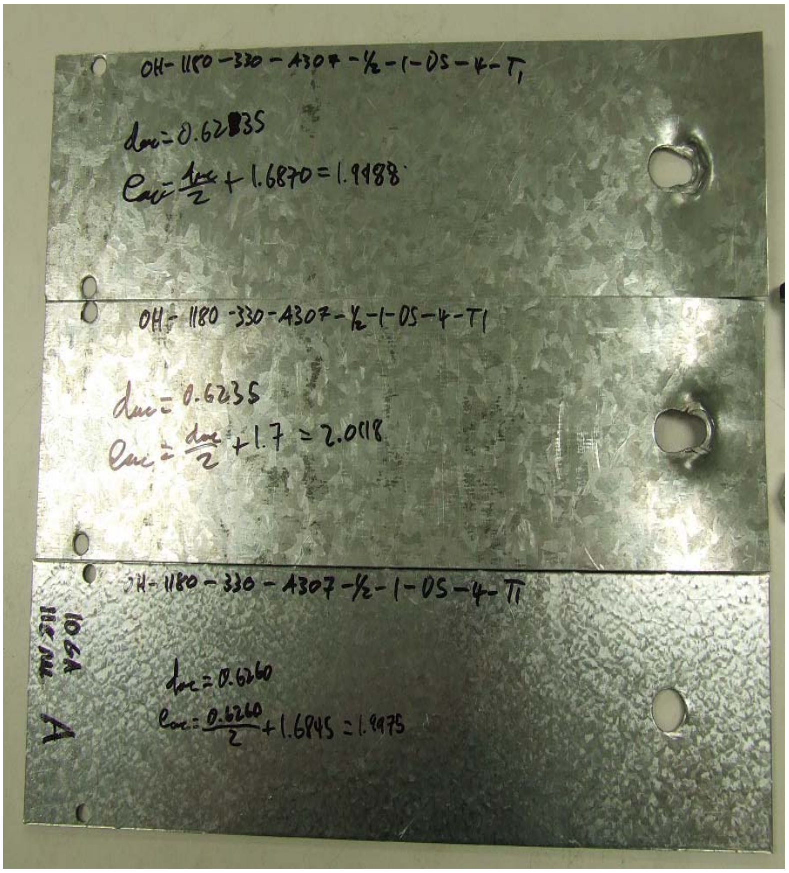
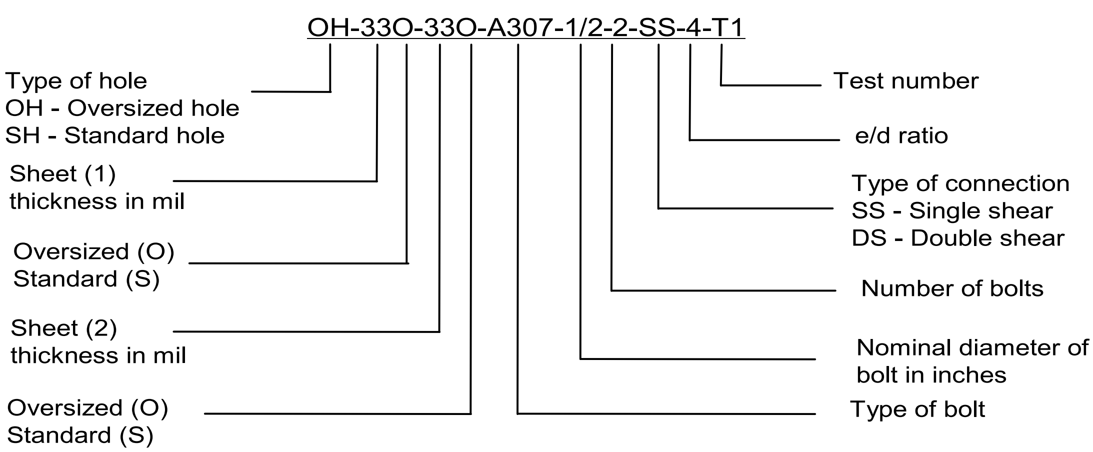


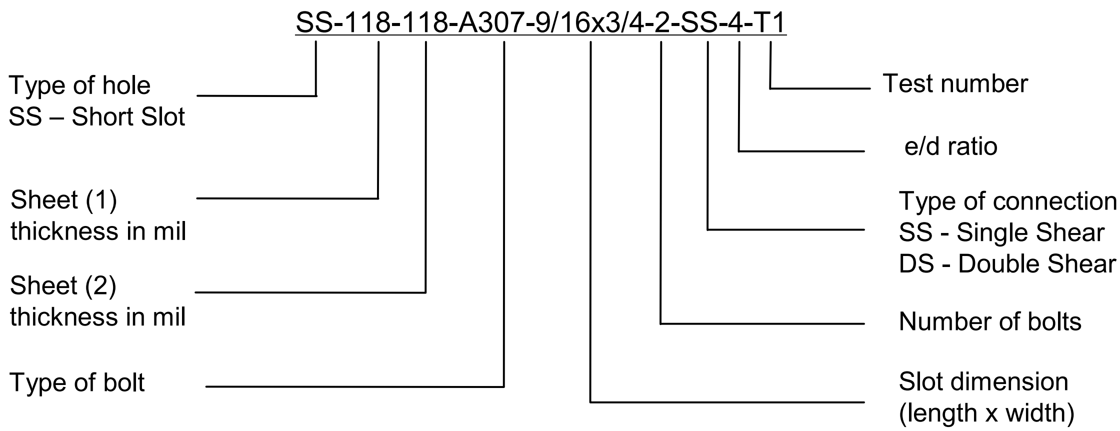
Figure 3.8 Information on specimens.

The specimens were labeled as the following.

For tests with oversized holes:



For tests with short slots:



The specimen configurations for this study are listed in Tables 3.2 to 3.3. For each specimen configuration, two identical tests were conducted. If the difference of the first two tests is greater than 10%, a third test will be performed. The percentage of difference was calculated as follows:

$$\frac{|\text{The Reading of test (1) - The Reading of test (2)}|}{|\text{The Reading of test(1)}|} \text{ x } 100$$

Table 3.2 Test Matrix for Connections with Oversize Holes

Sample	Sheet 1 (mil)	Sheet 2 (mil)	Steel Ductility[1]	Bolt Type	Bolt Diameter d (in.)	No. of Bolts	C. Type[2]	Hole conFigure.[3]	e/d	No. of Configure.
1	118	118	H	A325	1/2	1	S	O/O	1.5, 4	2
2	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	1/2	1	D	O/O	1.5, 4	2
13	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	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	1/2	2	D	O/O	1.5, 4	2
30	68	68	H	A325	1/2	2	D	O/O	1.5, 4	2
31	43	43	H	A307	1/2	2	D	O/O	1.5, 4	4
32	33	33	H	A307	1/4, 1/2	2	D	O/O	1.5, 4	2
33	118	33	H	A307	1/2	2	D	O/O	4	1
34	118	43	H	A307	1/2	2	D	O/O	4	1
35	33	33	L	A307	1/2	2	D	O/O	1.5, 4	2
36	43	43	L	A307	1/2	2	D	O/O	1.5, 4	2
									Total	76 configure. 152 tests

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.

Table 3.3 Test Matrix for Connections with AISI Short Slots (9/16” × 3/4”)

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 Configure.
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 configure. 38 tests

Table 3.4 Test Matrix for Connections with MBMA Short Slots (9/16” × 7/8”)

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 Configure.
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 configure. 38 tests

CHAPTER 4

TEST RESULTS

4.1. Coupon Tests for Material Properties

The tensile tests were conducted in a 20 kip universal testing machine, INSTRON, in a displacement control mode. First the machine and the LVDT were calibrated before conducting the tests. Table 4-1 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 4.1. Figure 4.1 shows the stress vs. strain curves of the tested steel sheet thicknesses. The test results indicate that the high ductile steels (33 mil, 43 mil, 68 mil, 118 mil) meet the minimum requirements for material ductility specified by NASPEC (2007). The current NASPEC 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, 39 mil) do not meet NASPEC'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 4.1 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

The 118 mil, 68 mil, 43 mil and 33 mil sheets' material is ASTM A653 SS Grade 33 with the following mechanical and chemical properties:

Heat# R46275, Yield 43.50 ksi, Tensile 54.20 ksi, Elongation% 37.40, N-Value 0.188, C% 0.040 - Mn% 0.320 - P% 0.009 - S% 0.012 - Al% 0.035 - Si% 0.008 - Cu% 0.040 - Ni% 0.020 - Cr% 0.030 - Mo% 0.004 - Sn% 0.011-N% 0.004 - V% 0.001- B% .0000 - Ti% 0.001 - Cb% .000.

The 30 mil and 39 mil low ductile cold-formed steel ASTM A875 HSLAS Grad 80 with the following mechanical and chemical properties:

Yield 80 ksi, Tensile 90 ksi, Elongation% 10, C% 0.02 - Mn% 1.65 - P% 0.000 - S% 0.035 - Cu% 0.20 - Ni% 0.20 - Cr% 0.15 - Mo% 0.16 - Sn% 0.011-N% 0.004 - V% 0.01- Ti% 0.01 - Cb% .005.

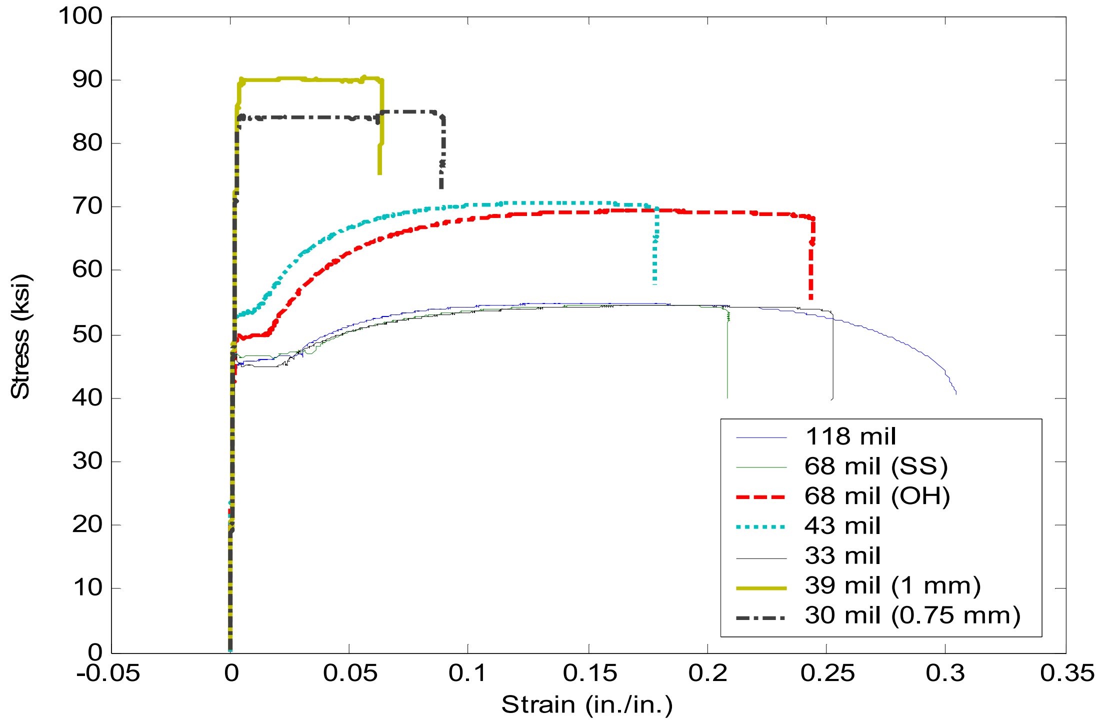


Figure 4.1 Stress-strain curves for tested materials.

The ASTM A307 Grade A and A 325 Bolts properties are listed in Table 4.2.

Table 4.2 ASTM A307 Grade A and A 325 Bolt Properties

Sizes	ASTM A307 Grade A 1/2 in. (13 threads/in.) 1/4 in. (20 threads/in.)	ASTM A325 Type 1 1/2 in. (13 threads/in.)
Tensile, ksi	60	120
Yield, ksi	--	92
Elong. %,	18	14
Chemical properties		
Carbon	0.33	0.55
Manganese	1.25	0.57
Phosphorus	0.041	0.048
Sulfur	0.15	0.058
Silicon	--	0.32

4.2. Tensile Tests on Bolted Connections Without Washers on Oversized Holes (Main Group)

4.2.1. Sheet Bearing Failure

Type II failure, the bearing failure of sheet, was experimentally tested by using the tensile tester. In fact, the bolted connections with edge distance e/d ≥ 3 were addressed. Tables 4.2, 4.3, 4.4, and 4.5 show the variables that were measured and tested, such as P_{test}, which is the tested peak load per bolt and "Δ" which is the hole's deformation that occurs at the peak load. Figures 4.2 and 4.3 respectively depict the resulted bearing failure mode on sheets with 43 mil thickness and single ½ in. A307 bolt. Figure 4.2 shows the bearing strength failure on single shear connection, whereas Figure 4.3 shows the failure on double shear connections. It can be observed that the bolt in the single shear connection was tilted to a large degree at failure, and the connected sheets curled outwards. Additionally, for some cases and throughout the tests, the hole's diameter was increased and elongated to a degree that the bolt's head was pulled through the hole and sunken. For Figure 4.3, the double shear connections, on the other hand, the bolt was almost perpendicular to the loading direction throughout the test, and the curling in the sheets was not as the connection with single shear connection. However, the curling effect was clear on the outside sheets more than the inside sheet.

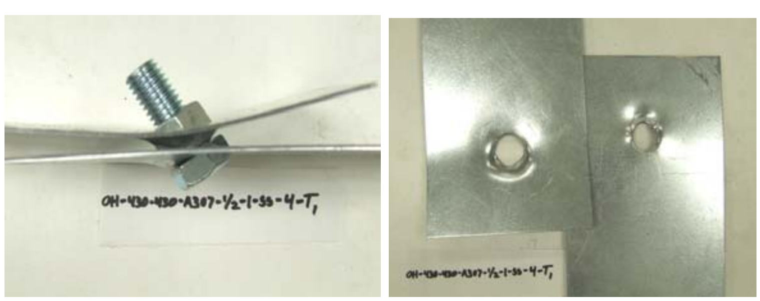


Figure 4.2 Sheet bearing failure of single shear connection OH-43O-43O-A307-1/2-1-SS-4-T1.

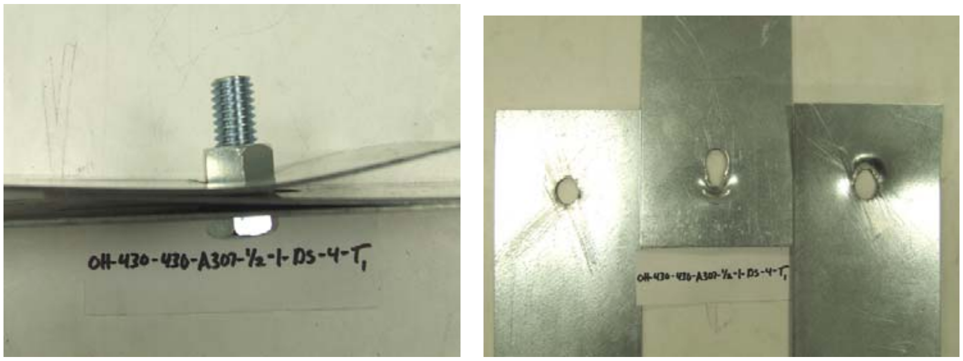


Figure 4.3 Sheet bearing failure of double shear connection OH-43O-43O-A307-1/2-1-DS-4-T1.

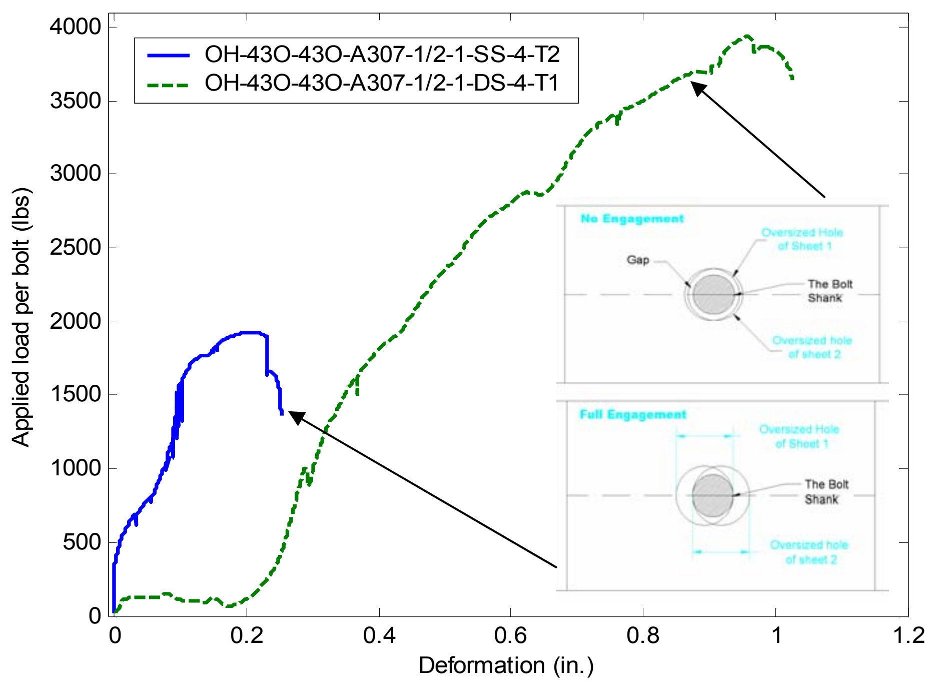


Figure 4.4 Load vs deformation curves for bearing strength tests with one bolt.

A plot of the applied load per bolt vs. the bolt deformation is shown in Figure 4.4. Two curves were plotted for the bolted connection with 43 mil thickness sheets having a single ½ in. A307 bolt. However, the blue curve represents the connection with a single shear configuration, whereas the red curve shows a double shear connection. The movement and the rotation of the bolt in the single shear connection during the test resulted in unsmooth loading curve; therefore, the bolt's movement and rotation plays a crucial role in any bolted connection test. On the other hand, the bolt's rotation and movement for the double shear connection was small; thus, a gradual and smooth curve was the result. From the plot, it was obvious that the single shear connection yielded considerably lower strength than the double shear connection. The diameter of the oversized hole was 5/8 in. which was greater than the diameter of the ½ in. bolt; therefore, the hole was deformed up to ¼ in. prior to the engagement of the bolt and the sheet in load bearing. As a result, throughout the tests, a slippage incident was occurred in most of the tests. The slippage was for a small distance before the load began to elevate gradually. For connections having ½ in. bolt, the bolt slippage could vary between 0 and ¼ in, whereas for connections having ¼ in. bolt, the slippage could vary from 0 to 1/8 in. In fact, the magnitude of the bolt slippage depends on the initial position of the bolt when installed in the sheets. Again, Figure 4.4 is nothing but two special cases. The single shear connection case, an instantaneous load increase after the test started was happened due to the fact that in the test's preparation phase the bolt was installed between the sheets where were engaged before tests. However, the double shear connection started to deform at 0.2 in. just before the engagement started the bearing forces were not so significant due to the gap between the hole and the bolt's shank. To avoid the influence by the initial bolt position, the hole deformation reported in this report was measured from the point at which the bolt and sheets were fully engaged and the gap between the bolt's shank and the holes was not there.

Figure 4.5 Sheet bearing failure of single shear connection OH-43O-43O-A307-1/2-2-SS-4-T1.

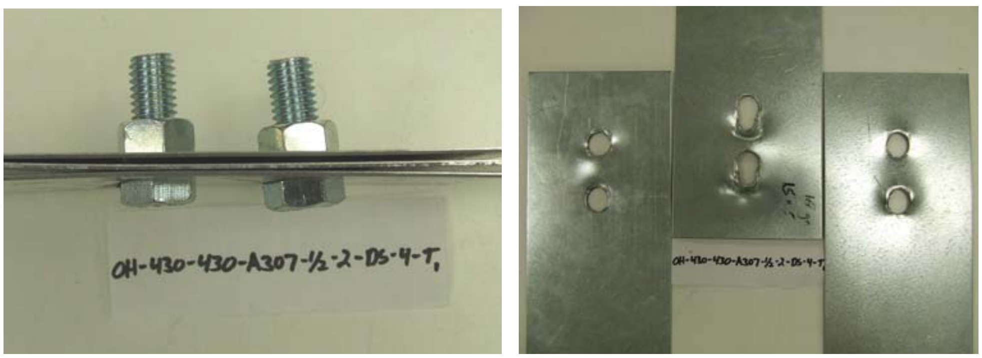


Figure 4.6 Sheet bearing failure of double shear connection OH-43O-43O-A307-1/2-2-DS-4-T1.

Figures 4.5 and 4.6 represent type II failure mode for 43 mil sheets having double bolts. Figure 4.5 shows a single shear double bolted connection test, whereas Figure 4.6 shows a double shear double bolts connection. A similar behavior was observed here, same as that of single bolt connection. Both Figures, Figure 4.5 and 4.6, show a typical sheet bearing failure. In Figure 4.6, the bolt was tilted and the outside sheets were curled; however, the bolts stayed straight in the double shear connection tests. Again, the holes were getting bigger throughout the tests due to the bearing forces; thus, the bolt's heads were pulled inside the holes. That resulted in a big tilted angle. On the other hand, on the double shear double bolts connection, the bolts' tilted angle was almost nothing due to the support that the inside sheet was given. However, the bearing load effect was obvious on the deformation of the holes in the inside sheet. Figure 4.7 shows the applied load per bolt vs. the hole deformation plot. One of the two curves, the green curve, depicts that the single shear connection had a bolt slippage of 0.13 in. before the bolt and holes in sheets were engaged, whereas the blue curve shows that the test had no pre-test gap between the bolt's shank and the holes in sheets so that it could bear the load immediately after the connection started to deform.

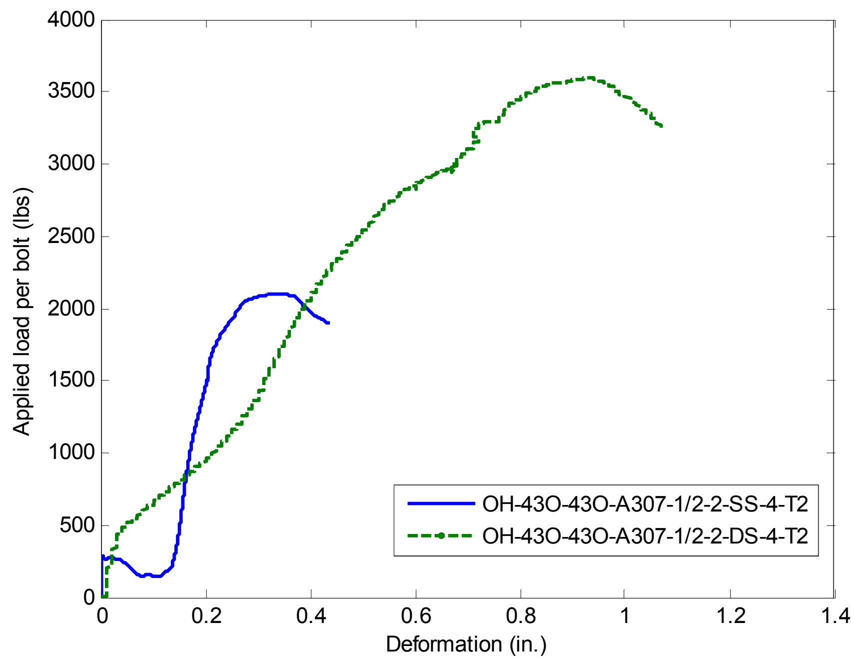


Figure 4.7 Load vs deformation curves for bearing strength tests with two bolts.

Tables 4.2, 4.3, 4.4, and 4.5 respectively show the test results for single shear single bolt connections with oversized hole where e/d >1.5, the test results for single shear double bolts connections with oversized hole where e/d >1.5, the test results for double shear single bolt connections with oversized hole where e/d >1.5, and the test results for double shear double bolts connections with oversized hole where e/d >1.5.

P_{test} and Δ were obtained from the tests and recorded in Tables 4.2, 4.3, 4.4, and 4.5, while P_{NAS}, the NASPEC value, and P_{New}, the proposed value, were calculated to know whether or not the value obtained by the existing method would still be applicable for such connections.

P_{NAS} and P_{NEW} were calculated by using Equation 1.2, $P_n = m_f C\ d\ t\ Fu$. The value of "d", which is the nominal bolt diameter, the value of "t", which is the uncoated sheet thickness, and the value of "F_u", which is the measured tensile strength of sheet from Table 4.1 were the same for both P_{NAS} and P_{NEW}. However, "C", the bearing factor, was calculated according to Table 2.2 for P_{NAS}, and according to Table 5.3 for P_{NEW}. In addition, "m_f", the modification factor, was selected to be 0.75 for single shear and 1.33 for double shear for P_{NAS}, whereas it was chosen to be 0.72 for single shear and 1.12 for double shear for P_{NEW}.

P_{test} was divided one time by the P_{NAS} and one time by the P_{NEW} and the results were recorded in the tables.

Table 4.2 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 4.3 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 4.4 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 4.5 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

4.2.2. Sheet Shear Failure

Type I, the shear failure of the sheet, was experimentally tested by using the tensile tester. In fact, the bolted connections with edge distance e/d = 1.5 was addressed. The test results, which are shown in Tables 4.6 and 4.7, show the observed tested peak load per bolt and the hole deformation at the peak load. Figure 4.8 shows the typical failure mode observed in the shear strength tests on 33 mil single shear, whereas Figure 4.9 shows the same connection but with double shear configuration. Both tests were using single ½ in. A307 bolt. The bolt tilted angle was significant in the single shear tests due to the eccentric loading applied on bolt. Consequently, the sheet visibly warped and piled up at bearing area, which is located in front of the hole. Additionally, a combined failure mode of shear and bearing, Type I and Type II, were achieved throughout the single shear tests, as shown in Figure 4.8. Figure 4.9, on the other hand, illustrates the results of the double shear tests, where a typical shear failure was observed on the inside sheet; in addition, the sheet was fractured and deformed tremendously at the hole edge. However, the bolt stayed perpendicular to the sheets and the bolt's tilted angle was very small. Figure 4.10 shows the applied load per bolt vs. the hole deformation plot. The two curves are for the 33 mil thickness bolted connection tests addressing the sheet shear failure mode. Both curves demonstrated bolt slippage of 0.1 in. Due to the big tilt angle of the bolt, the single shear connection had lost stiffness at the early stages more than the double shear connection had and finally the connection had failed at a lower load compared to that of the double shear connection.

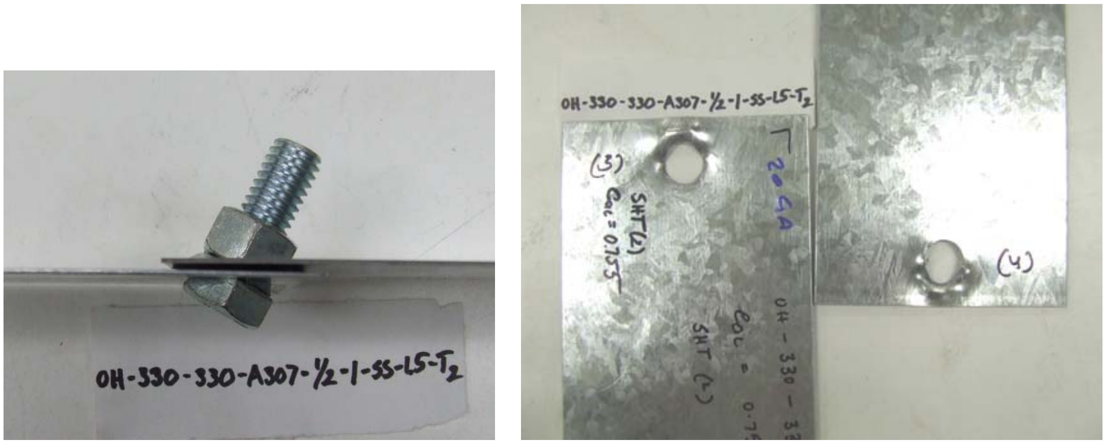


Figure 4.8 Sheet shear failure of single shear connection
OH-33O-33O-A307-1/2-1-SS-1.5-T2.

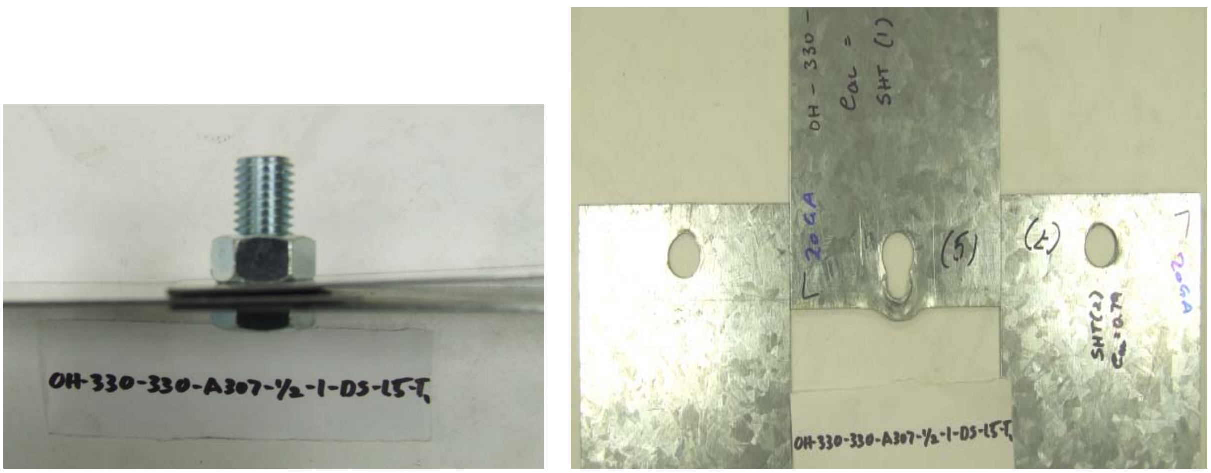


Figure 4.9 Sheet shear failure of double shear connection
OH-33O-33O-A307-1/2-1-DS-1.5-T1.

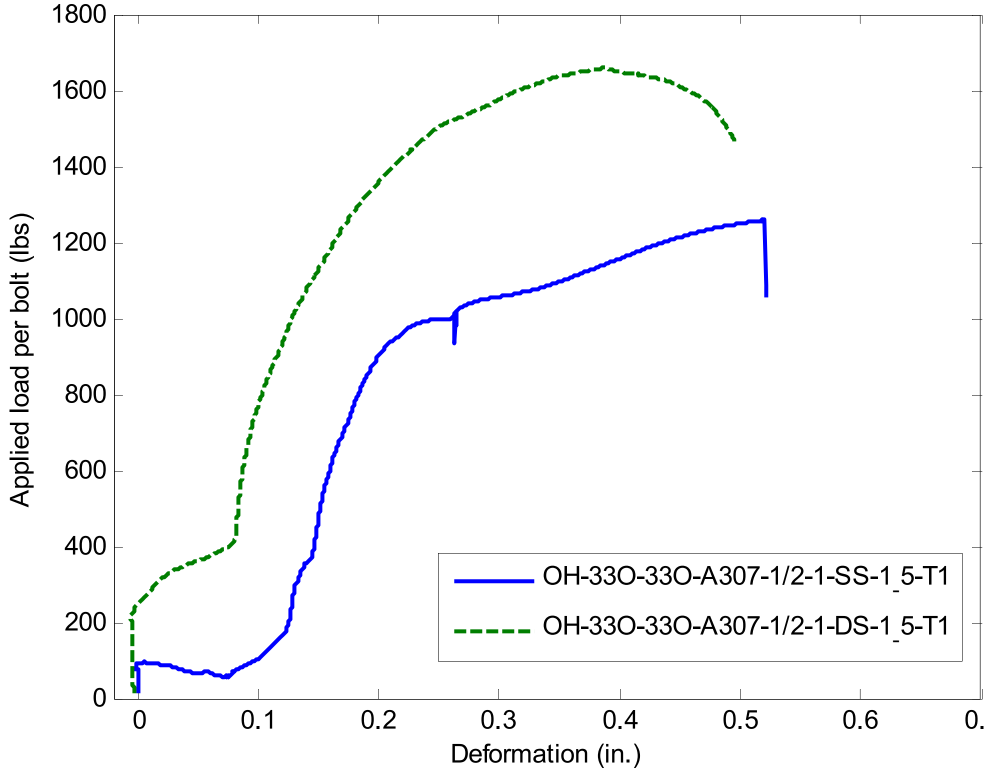


Figure 4.10 Load vs. deformation curves for sheet shear strength tests.

Tables 4.6 and 4.7 respectively show the test results for single shear single bolt connections with oversized hole where e/d =1.5 and the test results for double shear single bolt connections with oversized hole where e/d =1.5.

Again, P_{test} and Δ were obtained from the tests and recorded in the table, while P_{NAS}, the NASPEC value, was calculated to know whether or not the value obtained by the existing method would still be applicable for such connections.

P_{test} was divided by the P_{NAS} and the results were recorded in Tables 4.6 and 4.7.

Table 4.6 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 4.7 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

4.2.3. Sheet Bearing Failure and Sheet Shear Failure Combined

Specific configurations were addressed where two bolts were used in testes where e/d =1.5. When double bolts connections were used, two different failure modes were observed as predicted. The two holes were punched with the same diameter; however, the first hole was punched close to the edge of the sheet (the edge distance e/d = 1.5), and the second hole, as shown in section 3 Figure 3.7, was placed in a distance equals to 3 times of bolt diameter (3d) from the center of the first hole. Accordingly, it was observed that the sheet shear failure had occurred on the first hole and the sheet bearing failure had occurred on the second hole. A combination of failure modes was also observed throughout some tests occurred.

Figure 4.11 illustrates a typical failure mode on single shear connections. The two bolts were tilted to a great extent in the test and it forced the sheets to warp and pile up. It was noticed that a pure sheet shear failure was not observed on the first hole. There was an effect by bearing, however, to some degree. Again, bolts heads were inside the deformed holes. A typical failure mode observed on double shear connections was shown in Figure 4.12. The tilting angle of the two bolts was insignificant, and a combination of the sheet bearing and sheet shear failures were observed on the second hole and the first hole as well. Both of Figures 4.11 and 4.12 presented here address 33 mil thickness sheets, double bolts, single and double shear, connections..

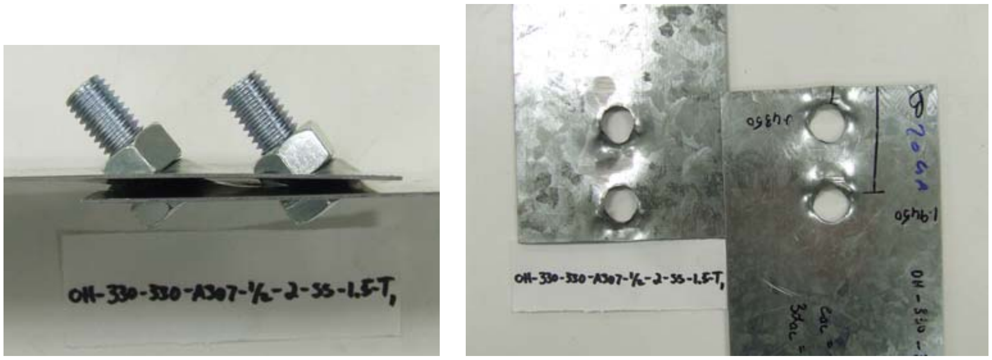


Figure 4.11 Failure mode of test OH-33O-33O-A307-1/2-2-SS-1.5-T1.

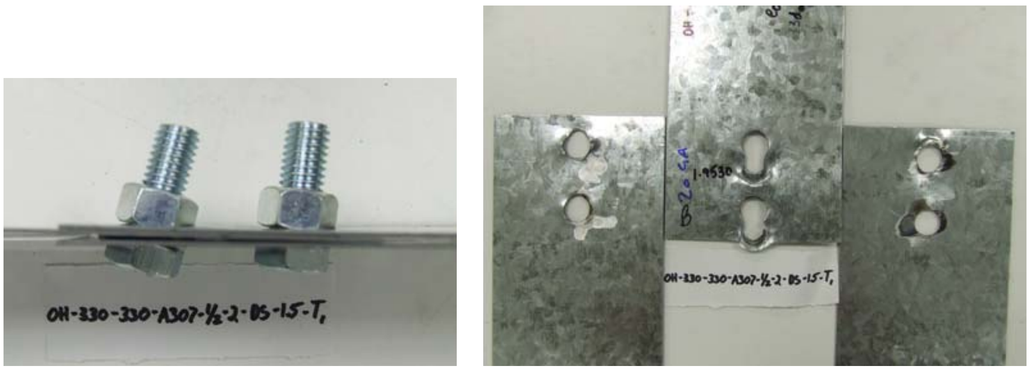


Figure 4.12 Failure mode of test OH-33O-33O-A307-1/2-2-DS-1.5-T1.

Tables 4.8 and 4.9 respectively list the test results for single shear double bolts connections with oversized hole where e/d =1.5 and the test results for double shear double bolts connections with oversized hole where e/d =1.5.

P_{test} and Δ were obtained from the tests and recorded in the table, while P_{NAS}, the NASPEC value, was calculated to know whether or not the value obtained by the existing method would still be applicable for such connections.

Table 4.8 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 4.9 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

4.3. 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 in. 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 4.10. Table 4.10 shows the additional tests on 33 mil and 43 mil single shear connections, where e/d > 1.5. P_{test} and Δ were obtained from the tests and recorded in the table, while P_{NAS}, the NASPEC value, was calculated to know whether or not the value obtained by the existing method would still be applicable for such connections. The method to calculate P_{NAS} and P_{NEW} is listed in the previous section.

Figures 4.13 and 4.14 respectively show the failure mode of the 43 mil thickness connections with washers on standard hole and oversized hole. Compared to the connections without washers, the connections with washers revealed lower tilting angle of the bolt and larger hole deformation which resulted in higher bearing strength. Figure 4.15, on the other hand, shows the failure mode of a 43 mil thickness connection without washer on standard hole where the bolt was tilted but the nut and bolt head did not go through the hole and the hole was not very much deformed compared to tests with washers.

Both the 43 mil sheets and the 33 mil were high ductile sheets. The 43 mil sheets have a yield strength Fy = 51.6 ksi and an ultimate strength of Fu = 70.3 ksi, whereas the 33 mil sheets have a yield strength Fy = 44.6 ksi and an ultimate strength Fu = 54.1 ksi. For the 1/2 in. bolt diameter the standard hole diameter was 9/16 in. while the oversized hole diameter was 5/8 in.

The washers that were used in the tests has an hole diameter of 0.57 in., an outside diameter of 1.37 in. and a thickness of 0.106 in.

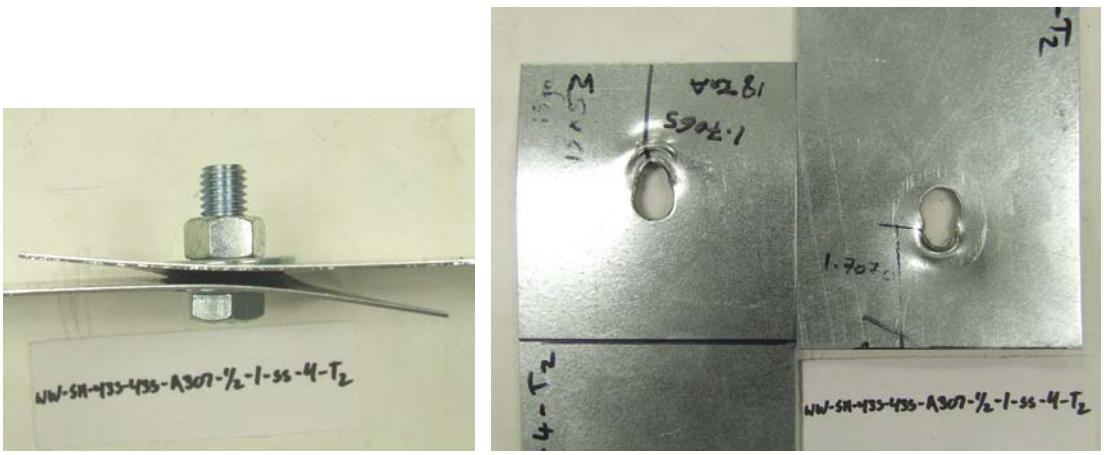


Figure 4.13 Failure mode of test WW-SH-43S-43S-A307-1/2-1-SS-4-T2.

Figure 4.14 Failure mode of test WW-OH-43O-43O-A307-1/2-1-SS-4-T1.

Table 4.10 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 ConFigure.	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

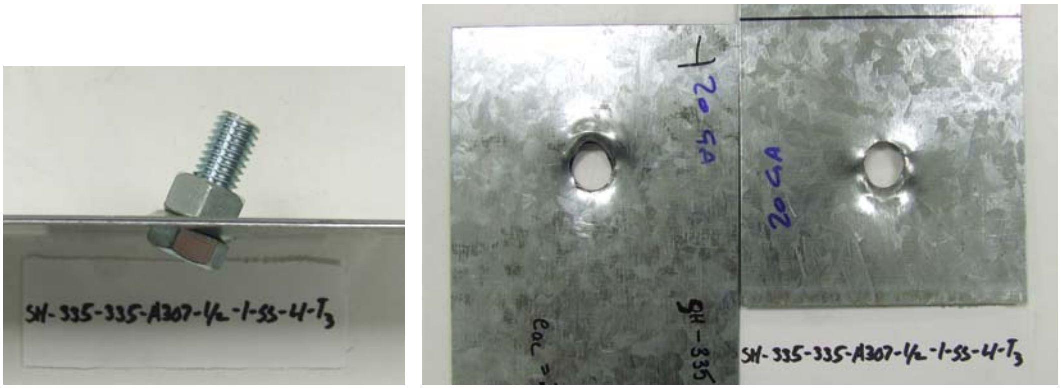


Figure 4.15 Failure mode of test SH-33S-33S-A307-1/2-1-SS-4-T3.

4.4. 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 in. diameter A307 Type A bolts. Two sizes of short slotted holes were investigated: 9/16 in. by 3/4 in. and 9/16 in. by 7/8 in. The research focused the first two types of failures: the sheet bearing failure and the sheet shear failure modes.

4.4.1. Sheet Bearing Failure

The bearing failure was investigated on tensile tests on connections with e/d = 4. The results are summarized in Tables 4.11 and 4.12 for single shear and Tables 4.13 and 4.14 for double shear. Tables 4.11, 4,12, 4,13, and 4.14 respectively show the test results for single shear single bolt connections with short slotted holes where e/d =4, test results for single shear double bolts connections with short slotted holes where e/d =4, the test results for double shear single bolt connections with short slotted holes where e/d =4, and the test results for double shear double bolts connections with short slotted holes where e/d =4.

P_{test} and Δ were obtained from the tests and recorded in the table, while P_{NAS}, the NASPEC value, was calculated to know whether or not the value obtained by the existing method would still be applicable for such connections. The calculation of P_{NAS} and P_{NEW} is shown in the Section 4.3.

Figure 4.16 illustrates a comparison of the applied load per bolt vs. hole deformation curves between the single shear single bolt connections in bearing. Figures 4.17 through 4.20 show the failure mode, of high ductile, 68 mil and 118 mil thicknesses single shear single bolt connections. It was observed that the bolt tilted to the highest degree in the single shear specimens and the bolt head and nut passed through the slotted hole causing the failure of the connections. However, the tilting angle of bolt was more crucial in the connections where slots were large in size; therefore, the connections with 9/16 in. × 7/8 in. slots' size yielded lower bearing strength than the connections with 9/16 in. ×3/4 in. slots' size.

Similarly, on the single shear double bolts tests where ½ in. A307 bolts were used, the connections with 9/16 in. × 7/8 in. slots' size yielded lower bearing strength than the connections with 9/16 in. ×3/4 in. slots' size.

Figures 4.21 and 4.22 show the bearing failure mode of the connections using 2 bolts with 9/16 in. × 3/4 in. slots size and 9/16"×7/8" slots size respectively. The bolts tilted to a great extent throughout both tests. The bolt heads and nuts went through the 9/16 in.× 7/8 in. slots and resulted in a separation of the two sheets, shown in Figure 4.22. The double bolts connections with smaller slot size (9/16 in.× 3/4 in.) gave higher bearing strength than the connections with larger slot size (9/16 in. ×7/8 in.).

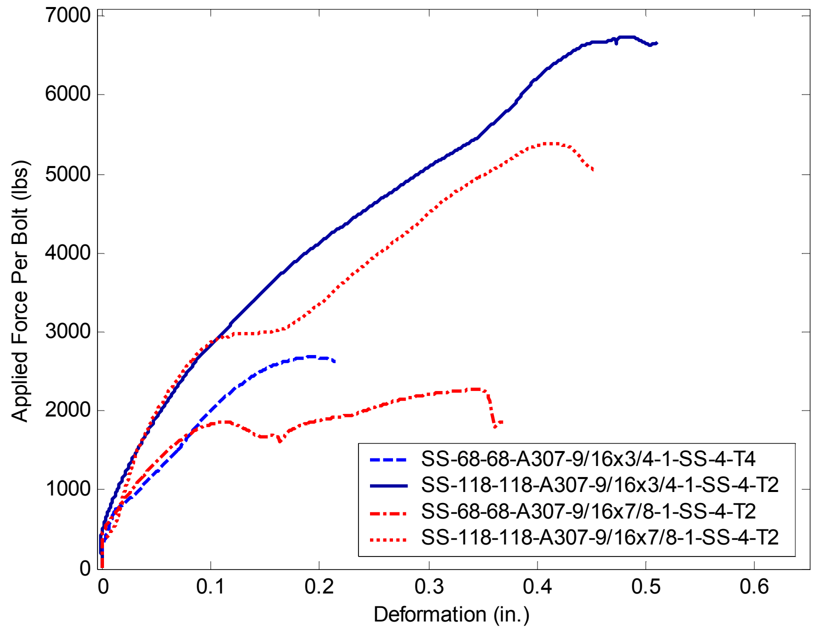


Figure 4.16 Load vs. deformation curves for single shear connections with single bolt, slotted holes in bearing,

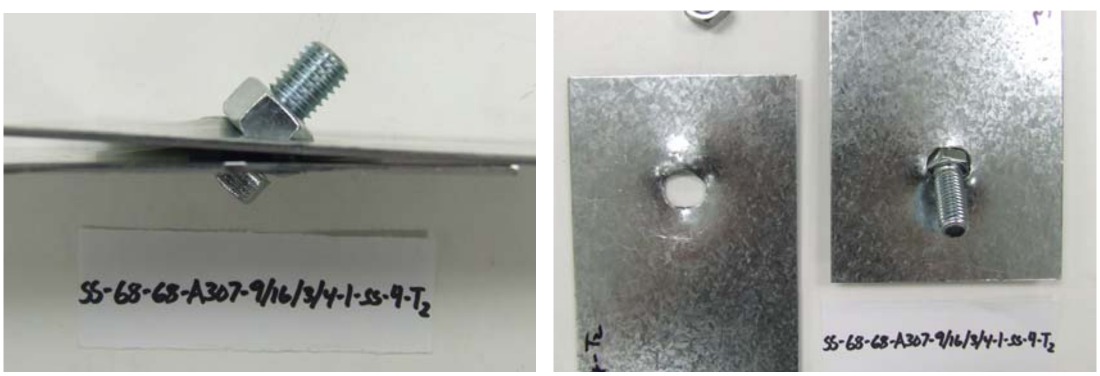


Figure 4.17 Failure mode of test SS-68-68-A307-9/16x3/4-1-SS-4-T2.

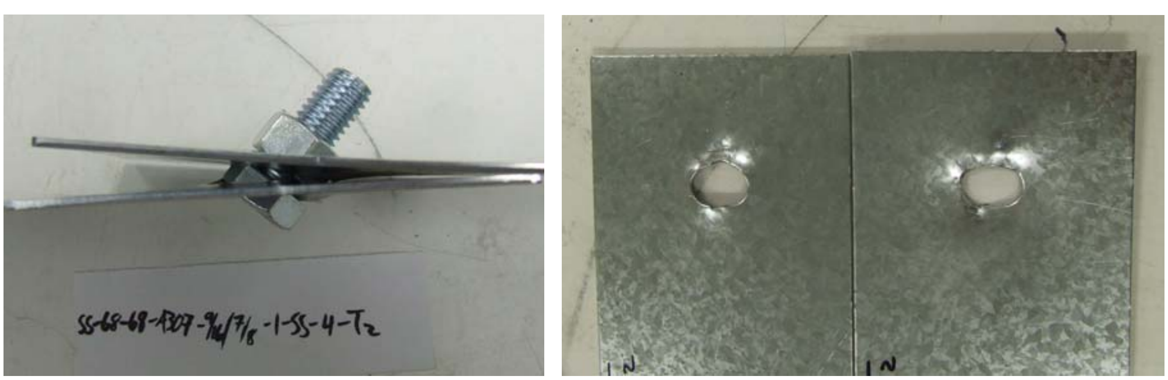


Figure 4.18 Failure mode of test SS-68-68-A307-9/16x7/8-1-SS-4-T2.

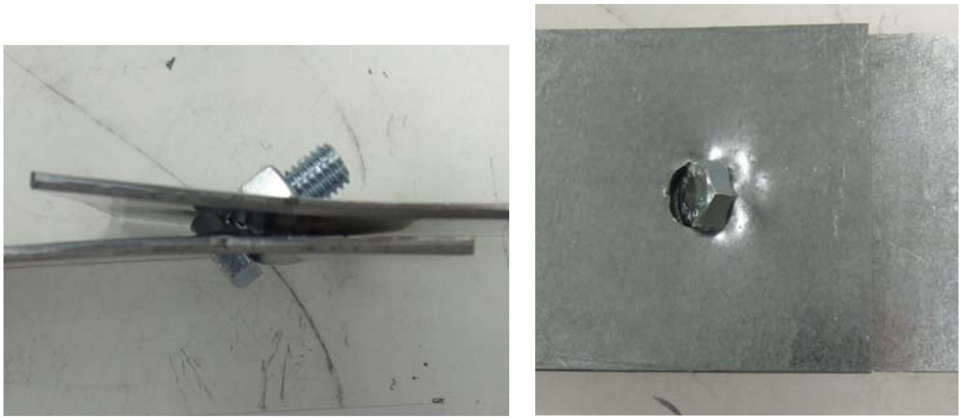


Figure 4.19 Failure mode of test SS-118-118-A307-9/16x3/4-1-SS-4-T2.

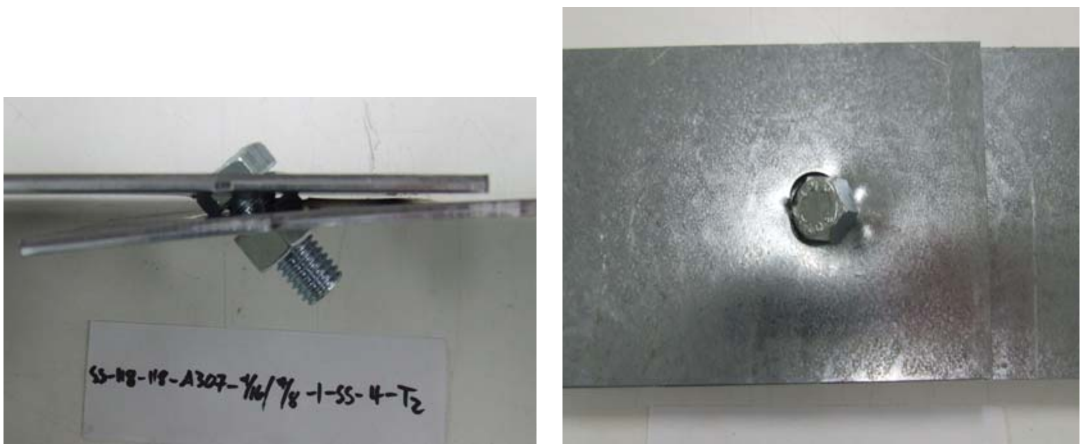


Figure 4.20 Failure mode of test SS-118-118-A307-9/16x7/8-1-SS-4-T2.

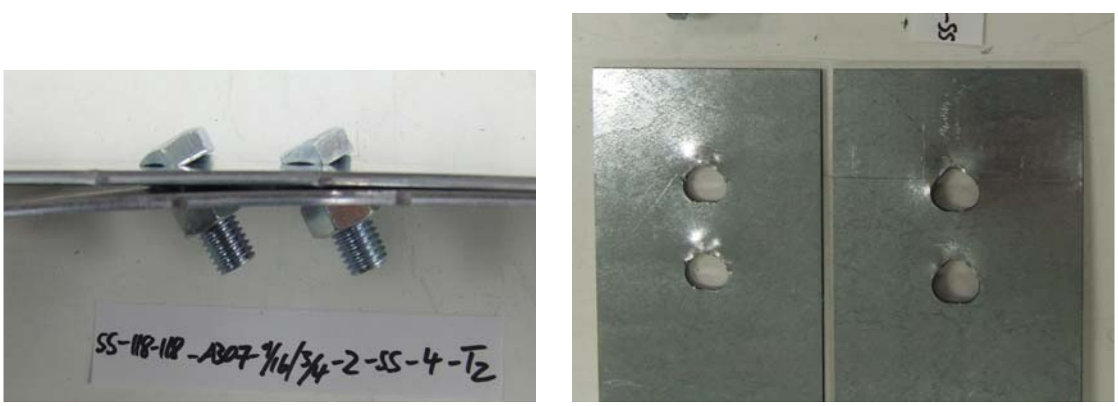


Figure 4.21 Failure mode of test SS-118-118-A307-9/16x3/4-2-SS-4-T2.

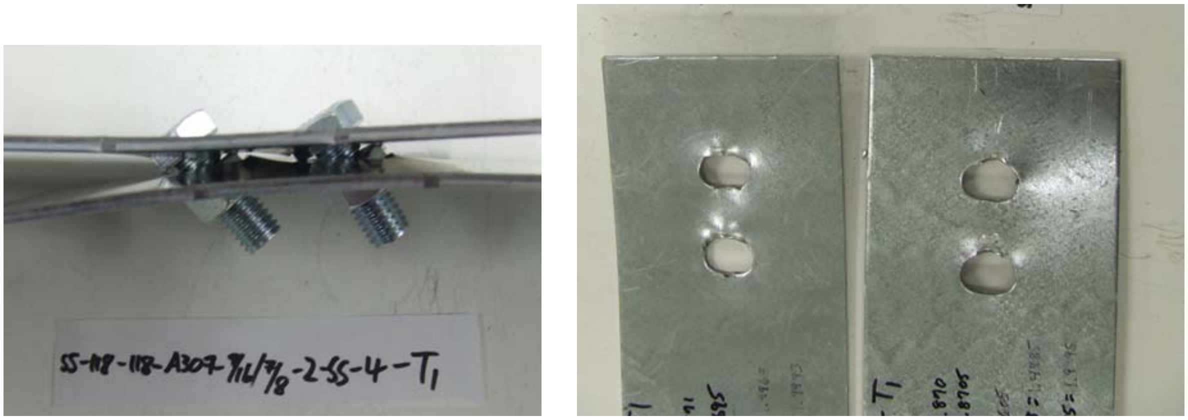


Figure 4.22 Failure mode of test SS-118-118-A307-9/16x7/8-2-SS-4-T1.

In this report, I had also investigated the behavior of using different sheet thickness in the same connection of single shear tests in bearing. When using two different sheet thicknesses in one connection the test results were recorded and compared. The test results are listed in Tables 4.11 and 4.12. Figures 4.23 and 4.24 demonstrate the failure mode of the connections using two different sheet thicknesses with single bolt and double bolts respectively. It was noticeably observed that the thinner sheet had larger deformation at the slotted hole and the nut or bolt head went through the thinner sheet. The thinner sheet had absorbed a huge amount of bearing load during the tests. It was found that the sheet thickness played a significant role in these tests.

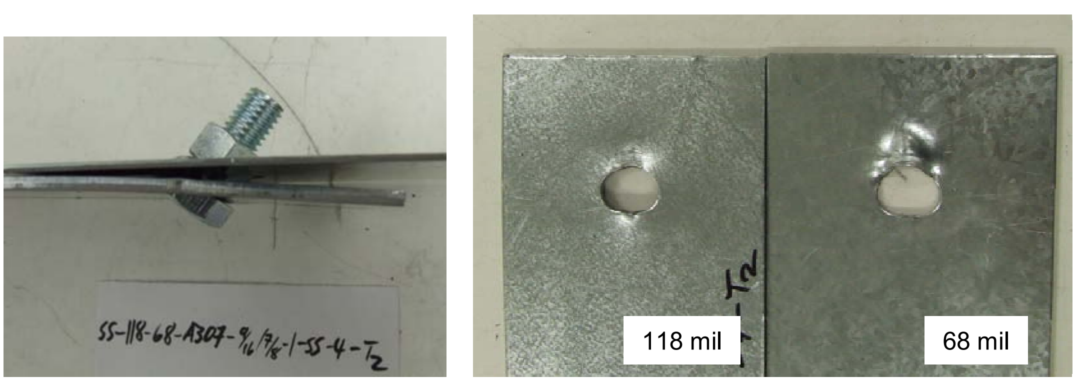


Figure 4.23 Failure mode of test SS-118-68-A307-9/16x7/8-1-SS-4-T2.

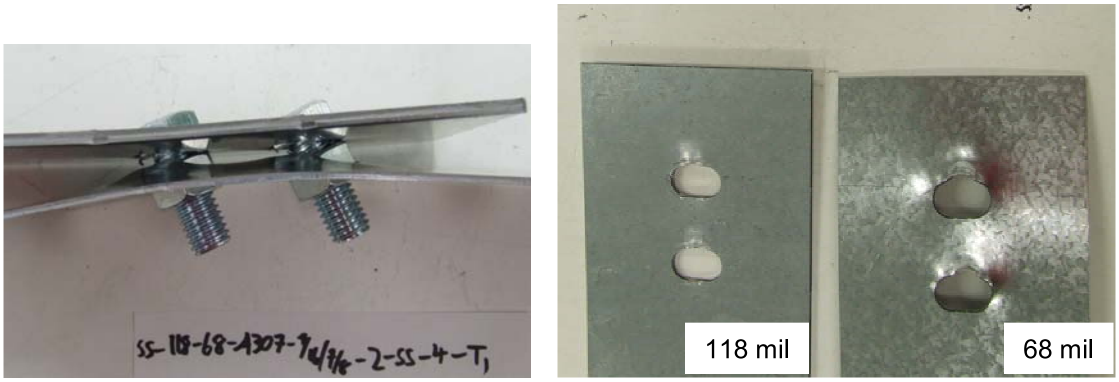


Figure 4.24 Failure mode of test SS-118-68-A307-9/16x7/8-2-SS-4-T1.

A series of tests were conducted to investigate the bearing strength of double shear single and double bolted connections without washers on short slotted holes. The sheet thicknesses were varied between 118 mil and 68 mil specimens. Some tests were conducted using one sheet thickness, whereas other tests were conducted using two different sheet thicknesses. The connections were having single and double ½: in. diameter A307 bolts. The test results are summarized in Tables 4.13 and 4.14 of this report. Figure 4.25 illustrates the applied load per bolt vs. hole sheet deformation plot. The plot comprises curves for double shear single bolt tests. Figure 4.26 through Figure 4.29 show the failure mode of typical118 mil and 68 mil double shear single bolt tests. The bolt remained perpendicular to the sheets throughout the double shear tests; therefore, the curves were smoother than the single shear tests. Typical bearing failure was observed on the inside sheet of double shear connections. The inside sheet was curled and piled up at the contact area with the bolt. For the tests where 118 mil sheets were used, 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 variation was small.

Table 4.11 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 4.12 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

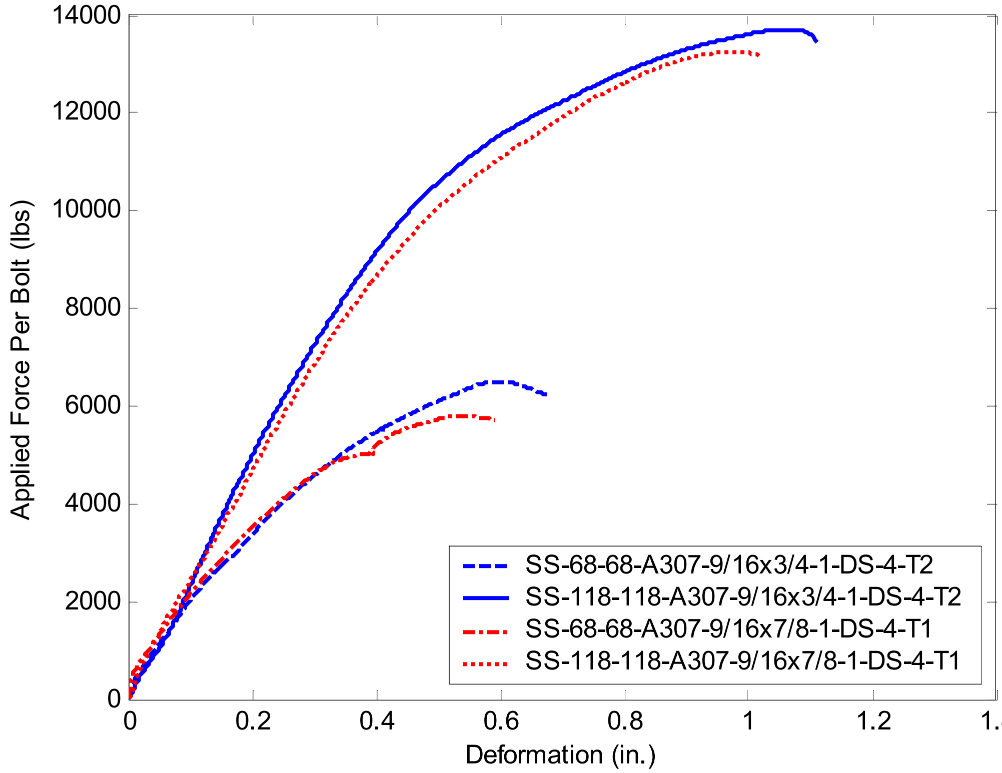


Figure 4.25 Load vs. deformation curves for single shear connections with single bolt, slotted holes in bearing.

Figure 4.26 Failure mode of test SS-68-68-A307-9/16x3/4-1-DS-4-T2.

Figure 4.27 Failure mode of test SS-68-68-A307-9/16x7/8-1-DS-4-T1.

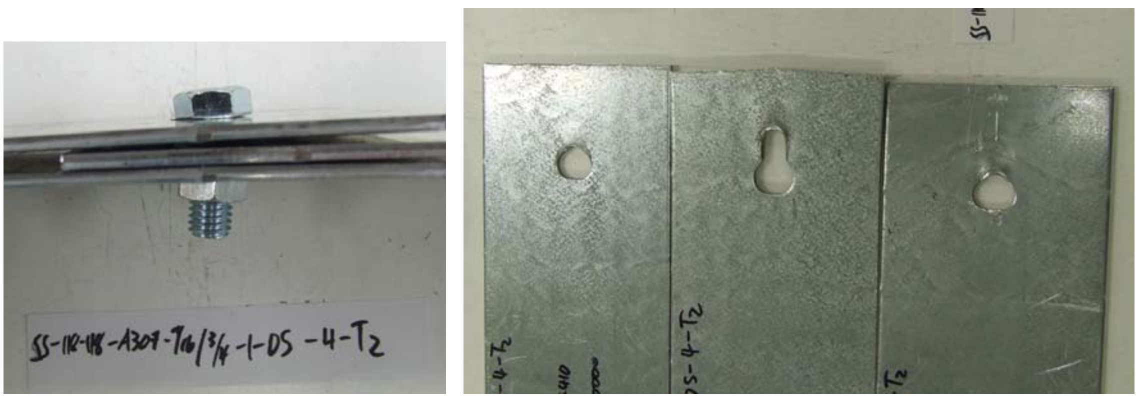


Figure 4.28 Failure mode of test SS-118-118-A307-9/16x3/4-1-DS-4-T2.

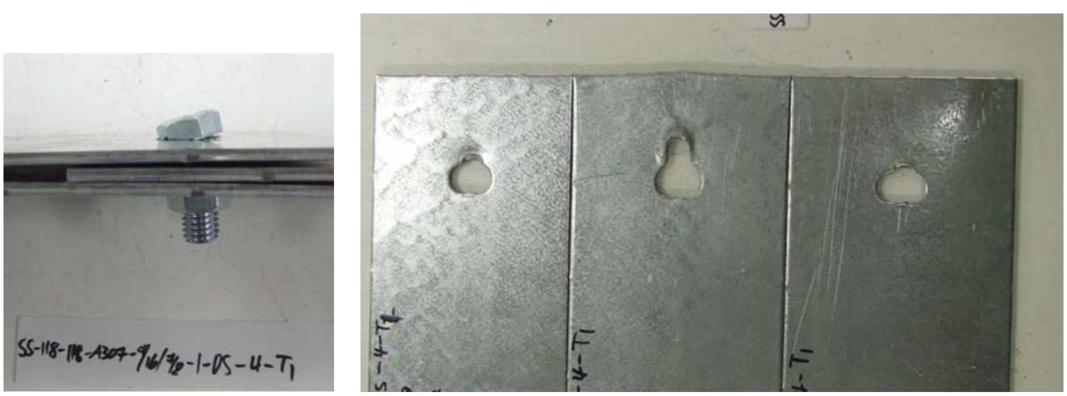


Figure 4.29 Failure mode of test SS-118-118-A307-9/16x7/8-1-DS-4-T1.

Table 4.13 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 4.14 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

4.4.2. Sheet Shear Failure

Type I failure, the sheet shear failure, of the bolted connections without washers on short slotted holes was experimentally examined by series of tests on single shear single bolt and double shear single bolt connections where the bolt diameter was ½ in. and e/d = 1.5. Figure 4.30 depicts the applied load per bolt vs. hole sheet deformation plot the include curves of two sheet thicknesses, 118 mil and 68 mil, with single shear connections in the sheet shear failure. The failure modes could be seen clearly in Figures 4.31, 4.32 and 4.33. When we examined the bolt movement and rotation behavior, we found that the bolt's tilt angle was significantly large, which means that the bolt was rotated, throughout the single shear tests and, therefore, the shear failure occurred. Again, due to the deformation on holes, the bolt head and nut passed through the slots, and the sheets separated at peak loads. It was concluded that the connections with AISI short slot sizes (9/16 in. × 3/4 in.) yield to higher shear strength than the connections with MBMA short slot sizes (9/16 in. × 7/8 in.).

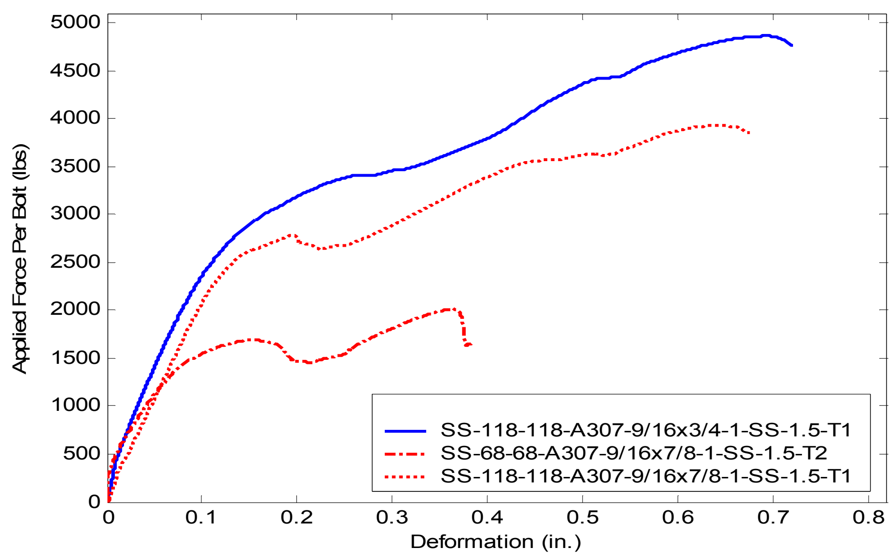


Figure 4.30 Load vs. deformation curves for single shear connections with single bolt, slotted holes, in shear.

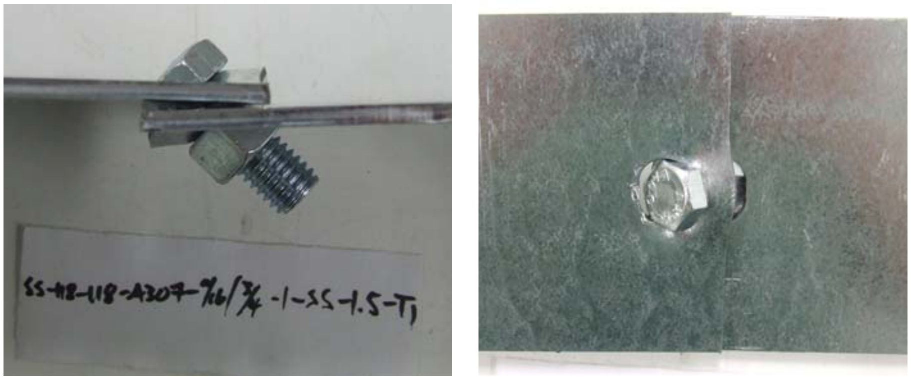


Figure 4.31 Failure mode of test SS-118-118-A307-9/16x3/4-1-SS-1.5-T1.

Figure 4.32 Failure mode of test SS-118-118-A307-9/16x7/8-1-SS-1.5-T1.

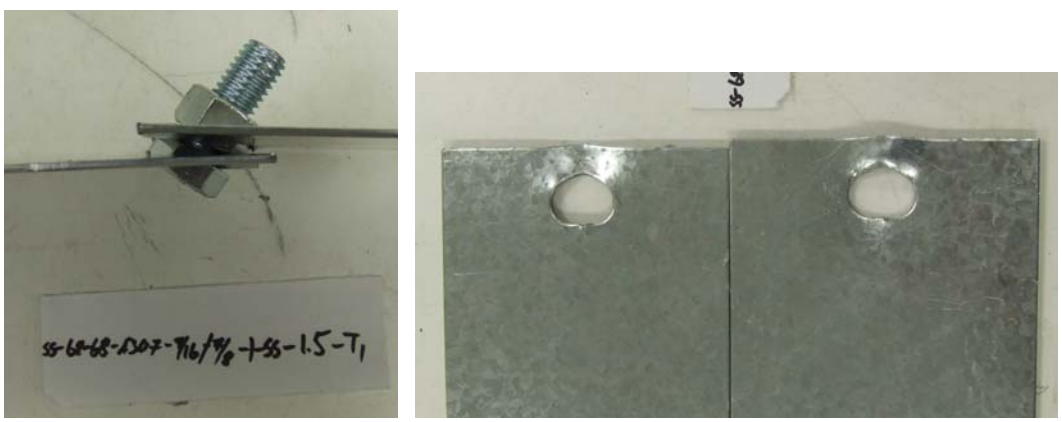


Figure 4.33 Failure mode of test SS-68-68-A307-9/16x7/8-1-SS-1.5-T1.

In this research, the sheet shear failure of the bolted connections without washers on short slotted holes was studied; therefore, a series of tests on single shear and double shear specimens with one ½ in. diameter A307 bolt where e/d = 1.5 were conducted. Figure 4.34 illustrates the applied load per bolt vs. the deformation plot that comprises curves for double shear tests in sheet shear failure. The failure mode could be clearly seen and observed in Figures 4.35 through 4.38, The bolt in all double shear tests stayed at a 90 degree angle to the sheets, no bolt tilting occurred during the tests, the rotation of the bolt was not appeared. Therefore, the curves were smooth. Typical sheet shear failure was attained on the inside sheet of the double shear specimens. The sheet was extended at the area in contact with the bolt. Similar mode of failure was detected when the connections had two different slot sizes. The connections with 9/16 in. ×3/4 in. slot yielded somewhat higher shear strength than the connections with 9/16 in.×3/4 in., but the variation was small. The test results for the sheet shear failure are summarized in Tables 4.15 and 4.16 for single shear and double shear respectively.

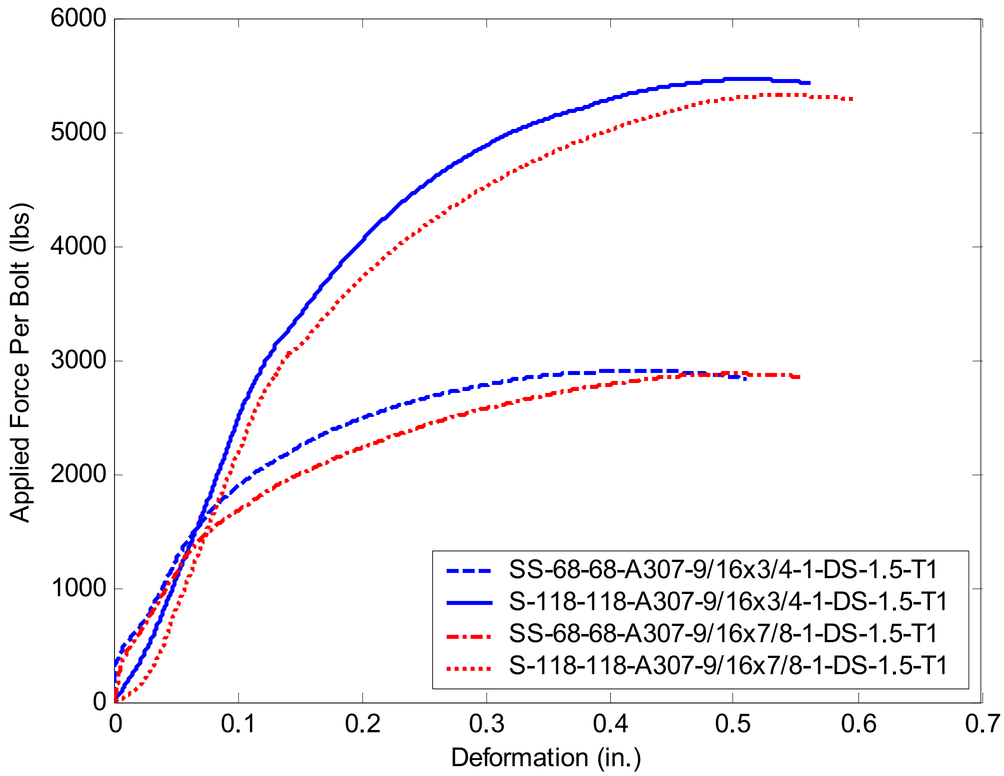


Figure 4.34 Load vs. deformation curves for double shear connections with single bolt, slotted holes, in shear.

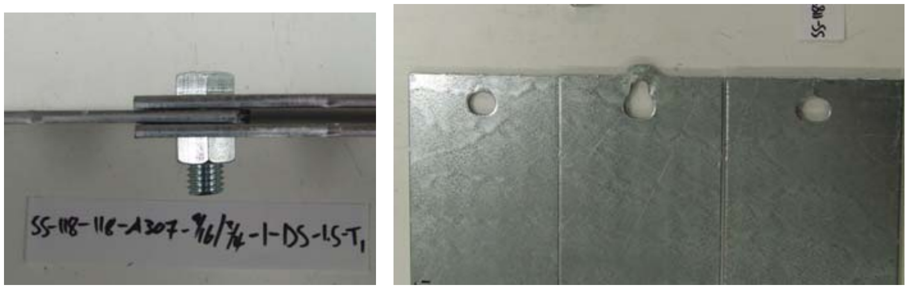


Figure 4.35 Failure mode of test SS-118-118-A307-9/16x3/4-1-DS-1.5-T1.

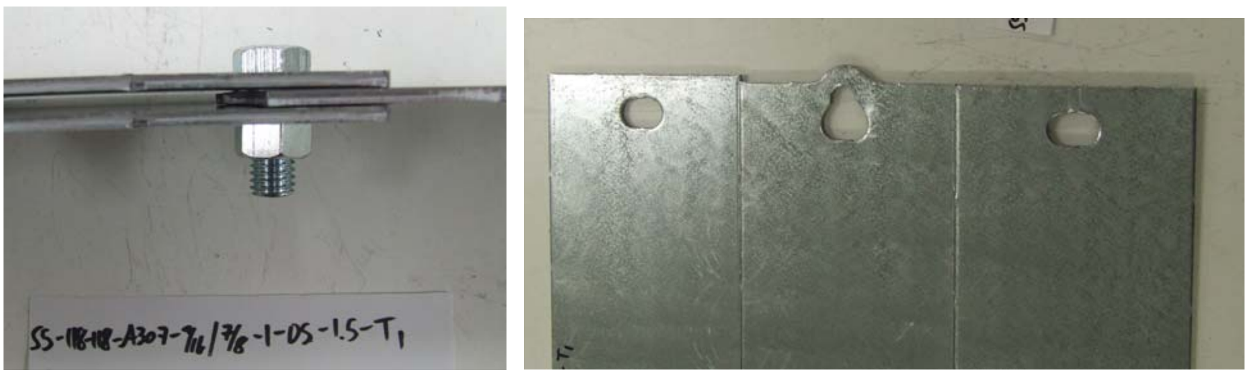


Figure 4.36 Failure mode of test SS-118-118-A307-9/16x7/8-1-DS-1.5-T1.

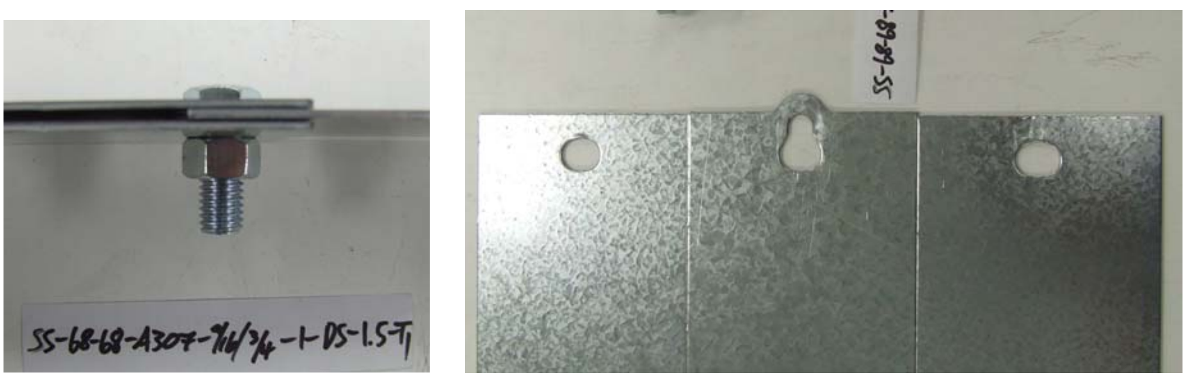


Figure 4.37 Failure mode of test SS-68-68-A307-9/16x3/4-1-DS-1.5-T1.

Figure 4.38 Failure mode of test SS-68-68-A307-9/16x7/8-1-DS-1.5-T1.

Table 4.15 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
7	SS-68-68-A307-9/16/3/4-1-SS-1.5-T1	68	68	0.5	7.16	0.75	54.5	2554	0.446	0.71
8	SS-68-68-A307-9/16/3/4-1-SS-1.5-T2	68	68	0.5	7.16	0.75	54.5	2456	0.431	0.68

Table 4.16 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

4.4.3. Sheet Bearing Failure and Sheet Shear Failure Combined

I conducted a series of tests using a thickness of 68mil with single shear and 1/2 in. diameter A307 bolts. During the bolts installation phase, one bolt was installed into the hole that had an edge distance e/d = 1.5, whereas the second bolt was placed in the hole that had a distance of 3 times of the bolt diameter (3d) from the center of the first hole. Upon that configuration, the sheet shear failure occurred at the first hole, the hole that had an e/d =1.5, and the sheet bearing failure occurred at the second hole. That is clearly demonstrated in Figures 4.39 and 4.40. A typical failure mode on single shear connections with 9/16 in. × 3/4 in. slots and 9/16 in. ×7/8 in. slots is shown in Figures 1.39 and 4.40 respectively. The bolts tilt angles were large and the nut and the bolt's head went through the elongated slots which, therefore, caused the separation of the two sheets. Again, the effect of the bolts rotation was obvious. It was found that the connections with smaller short slotted holes yielded higher strength than the connections with larger short slotted holes. Table 4.17 summarizes the test results of this specific configuration.

Figure 4.39 Failure mode of test SS-68-68-A307-9/16x3/4-2-SS-1.5-T3.

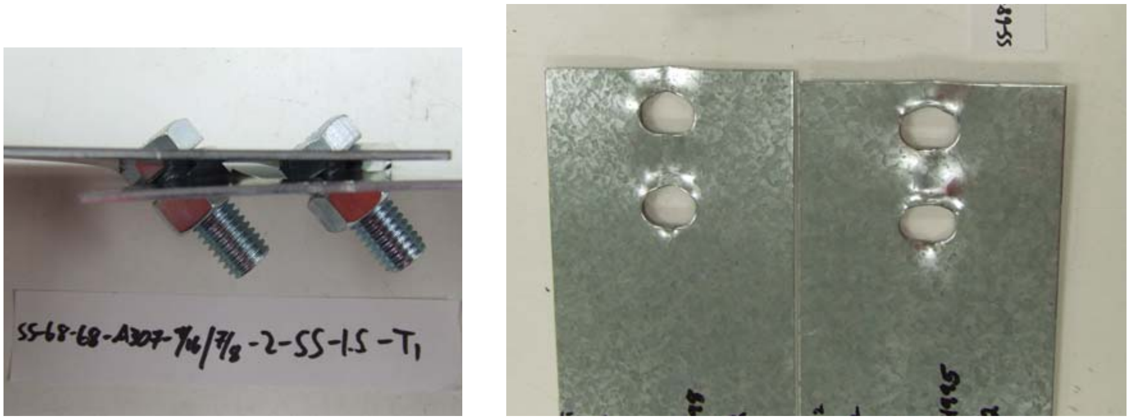


Figure 4.40 Failure mode of test SS-68-68-A307-9/16x7/8-2-SS-1.5-T1.

Table 4.17 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	0.794
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	0.905
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	0.919
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	0.707
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	0.678

CHAPTER 5

DISCUSSION

5.1. Sheet Bearing Strength of Bolted Connections Without Washers on Oversized Holes

The results were compared to the NASPEC (2007). In particular, the resulted values of bearing strength for bolted connections with oversized holes with e/d greater than 3 were evaluated and compared to the calculated bearing strength for bolted connections without washers on standard holes using NASPEC (2007). As mentioned earlier, the current NASPEC (2007) utilizes two design factors, the modification factor m_f and the bearing factor C, to distinguish and report different bolted connections configurations. A unified bearing factor formula, listed in Table 2.2, is employed in NASPEC (2007) for both single shear and double shear bolted connections.

Different values were applied for the modification factor m_f. According to NASPEC (2007), the modification factor m_f= 0.75 for single shear connections without washer on standard hole, whereas m_f=1.33 for the inside sheet of double shear connections without washer.

Figure 5.1 shows the comparison of the examined bearing factor C with the NASPEC (2007) method, table 2.2, and Waterloo's C equations for single shear connections, table 2.1. The equation $C = P_{test} / (m_f\, d\, t\, F_u)$ was used to calculate the tested bearing factor C where m_f = 0.75 (Single Shear Connection). The Figure also confirms that for single shear bolted connections with d/t larger than 7, the tested bearing strength is lower than the NASPEC (2007) predictions. On the other hand, by comparing the results to Waterloo's method, we found that most of the tested values were also lower than the Waterloo predictions. Not only that but also the plot shows that the bearing strength values of the bolted connections with single bolt were in close proximity to the bearing strength values of the same connections with double bolts. Looking into the behavior of the low ductile steel we can observe that the low ductile steel connections data results, which have solid symbols in Figure 5.1, are all gathered at the bottom of the whole data pool; however, the results still inside the boundary. Consequently, it can be observed that the selected low ductile steel materials in this research and the high ductile steel materials, in terms of predicting the bearing strength for bolted connections behavior, can be treated equally.

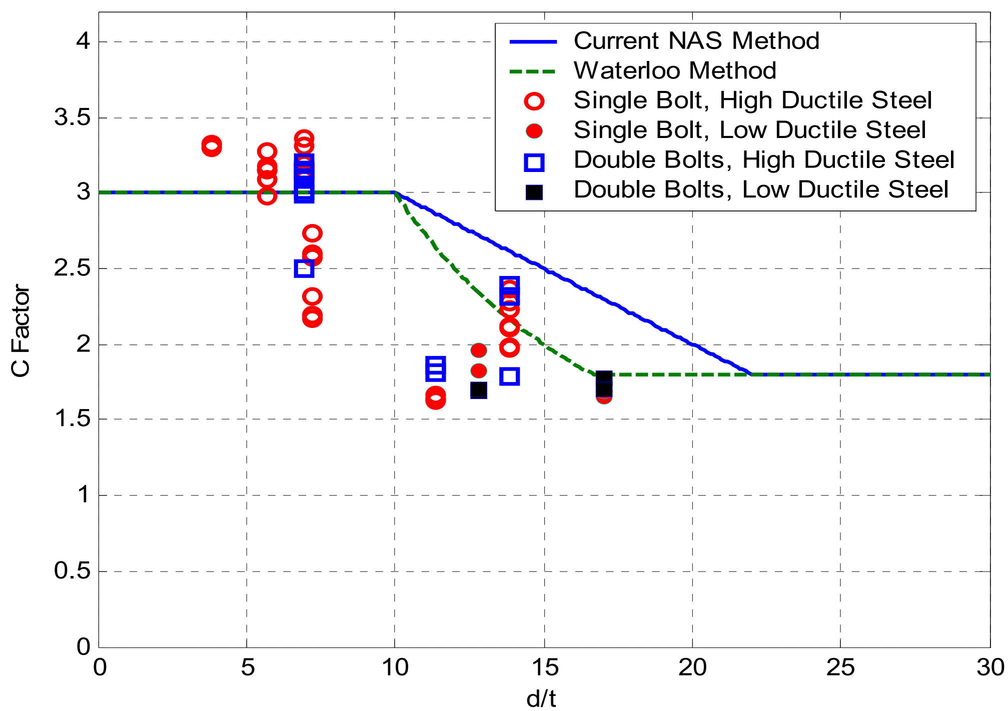


Figure 5.1 C vs d/t for bearing strength test on single shear connections with oversized holes.

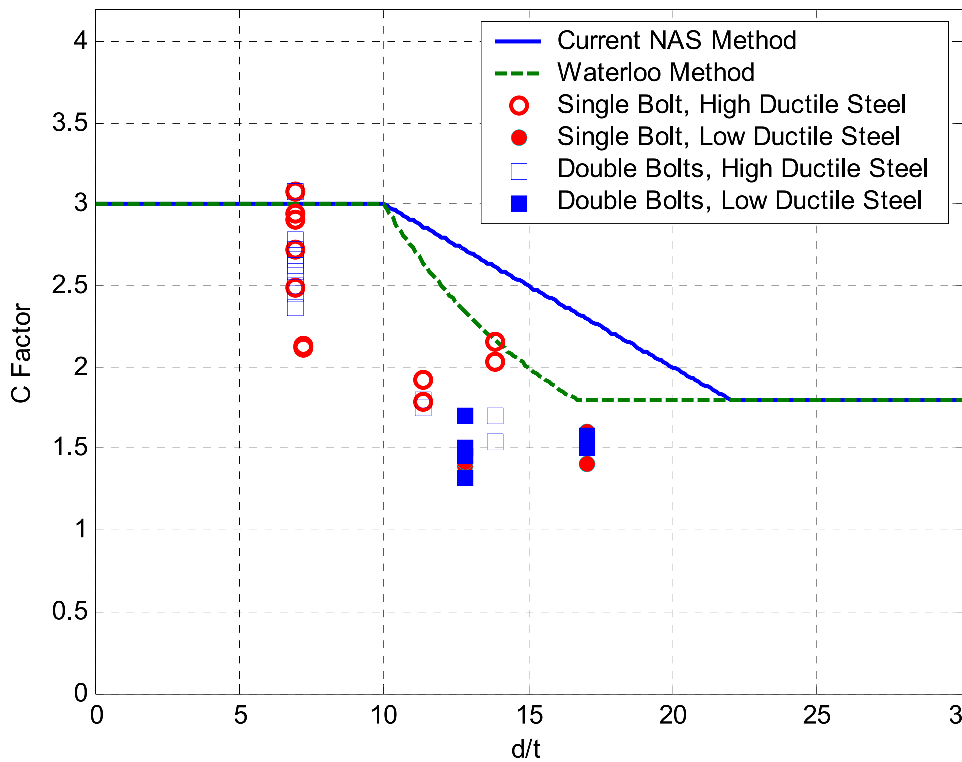


Figure 5.2 C vs d/t for bearing strength test on double shear connections with oversized holes.

On the other hand, Figure 5.2 shows a plot that represents a comparison of the examined bearing factor C with the NASPEC (2007) method, table 2.2, and Waterloo's C equations for double shear connections, table 2.1. The tested bearing factors were calculated by the same equation for single shear connection; however, the modification factor m_f was equal to1.33 in this case. Using the same method we used for single shear connections, we found that the majority of the double shear connections data results with oversized holes gave consistently lower bearing strength with compare to the NASPEC (2007) and Waterloo calculations for connections with standard holes. Nevertheless, the tested bearing factors C for single and double bolt connections were close to some extent. It can be observed from Figure 5.2 that the material ductility plays an important role throughout these tests. The Figure shows that the low ductile steel connections have lower tested bearing factors than the high ductile steel connections. However, the difference is not that crucial and not adequately significant to distinguish the two types of steel into two trends.

Generally, we can conclude from the test results that the cold-formed steel bolted connections without washers on oversized holes yield methodically lower bearing strength comparing to the calculated values by the current NASPEC 2007 and Waterloo methods for connections without washers on standard holes. Chapter 4: Tables 4.2, 4.3, 4.4, and 4.5 listed the test-to-NASPEC prediction ratios. The average test-to-predicted ratio for the sheet bearing strength was 0.87 for single shear connections, whereas the ratio was 0.75 for the double shear connections. Additionally, Tables 5.1 and 5.2 summarize the average ratio for the overall tests and breakdowns according to the number of bolts and the steel ductility.

Table 5.1 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 5.2 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

From the test data results for the bearing strength, a new method was proposed to calculate the bearing factor, C, and the modification factor m_f to accurately calculate the bearing strength of cold-formed steel bolted connections without washers on oversized holes. The proposed method is listed in Table 5.3 and 5.4 respectively. Those tables summarize the proposed factors for the single and double shear connections. On the other hand, the same bearing strength calculated by equation (Eq. 6.2) from NASPEC (2007) was still utilized for connections with oversized holes. However, the factors were substituted by the newly proposed ones.

Table 5.3 Proposed Bearing Factor, C, for Bolted Connections with Oversized Holes

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

Table 5.4 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

A comparison between the test results and the two design methods for the single shear and double shear connections are respectively illustrated in Figures 5.3 and 5.4. The y-axis represents the ratio of the nominal bearing strength for the design methods to the product of tensile strength, the bolt diameter and the sheet thickness, which can be expressed as $P/(F_u\ d\ t)$. In other words, the ratio stands for the peak load per bolt for the test results. As it is shown in Figures 5.3 and 5.4, the proposed design method has a reasonable agreement with the test results for both single and double shear bearing connections. The calculated 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. Both the single shear and the double shear connections have s standard deviation of 0.13. In addition, the newly proposed design method can also be used for both low and high ductile steel connections.

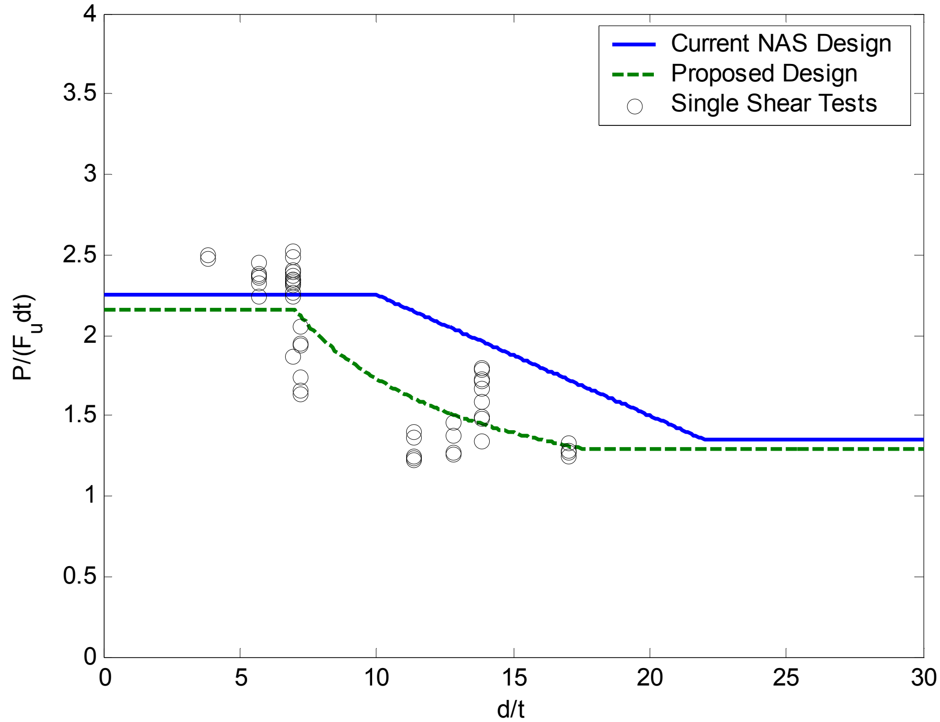


Figure 5.3 Test results vs. design methods for single shear connections with oversized holes.

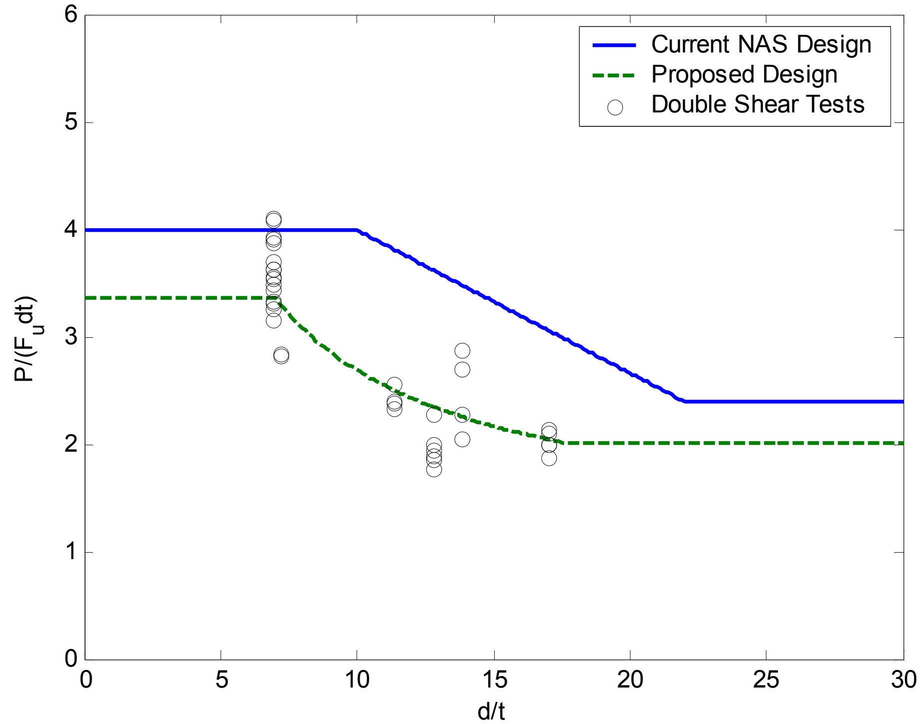


Figure 5.4 Test results vs. design methods for double shear connections with oversized holes.

5.2. Sheet Shear Strength of Bolted Connections Without Washers on Oversized Holes

A unified equation (Eq. 1.1) for the sheet shear strength for all bolted connections with standard holes is used by the NASPEC (2007). Tables 4.6 and 4.7 summarize the test-to-NASPEC prediction ratio for each shear strength test. A comparison of the tested shear strengths with the NASPEC (2007) predictions (Eq. 1.1) is shown in Figure 5.5. The plot shows that the current NASPEC (2007) provisions for the sheet shear strength of bolted connections on standard holes conform to the test results for connections without washer on oversized holes. The average test-to-NASPEC prediction ratio for all tests is 1.05 with a standard deviation of 0.22. In addition, no major difference was found between the single and double shear connections in terms of the sheet shear strength. The NASPEC (2007) grants fairly good prediction for the sheet shear strength for low ductile steel connections. The average test-to-NASPEC prediction ratio for the low ductile steel is 0.93 with a standard deviation of 0.11. Generally, the current NASPEC (2007) design method can be utilized in the bolted connections without washers on oversized holes. Table 5.5 gives the details of the test-to-predicted ratios.

Table 5.5 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

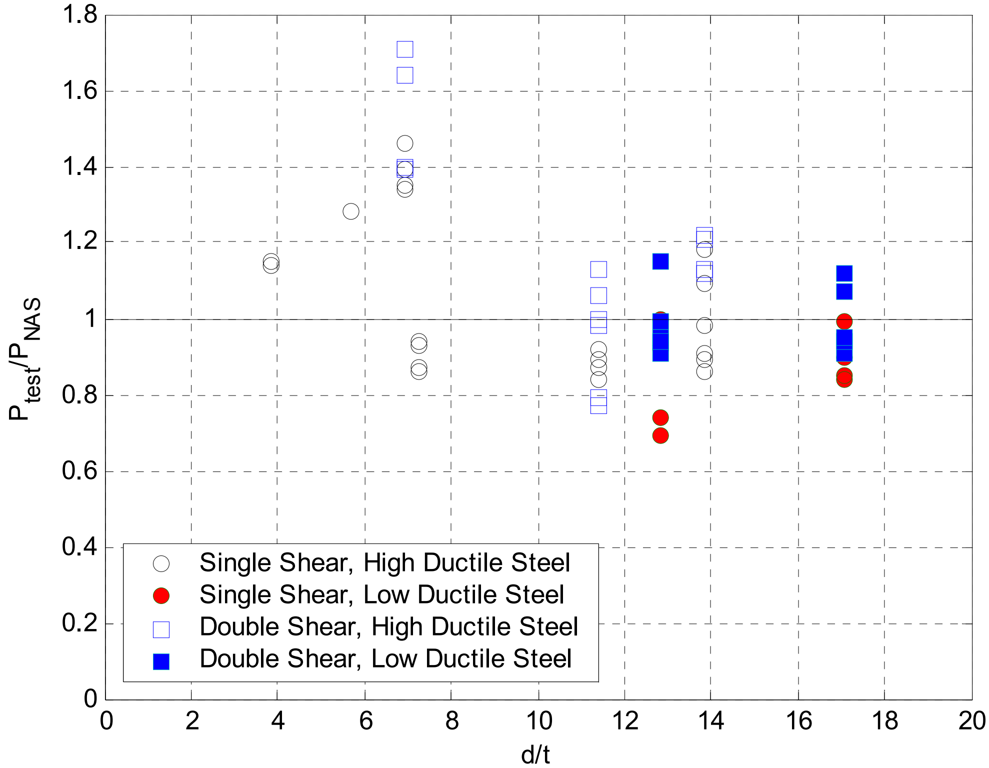


Figure 5.5 P_{test}/P_{NAS} vs d/t for sheet shear strength of connections with oversized holes.

5.3. Low Ductile vs High Ductile Steel

As we have seen earlier, Figures 5.1 and 5.2 respectively show comparisons of the bearing strength tests with the design equations for single shear and double shear. Filled or solid symbols are used for the low ductile steel tests, whereas unfilled symbols are used for the high ductile steel tests in order to visibly monitor their behavior. The low ductile steel data results are located in the lower bound of the whole test point set; however, they are not separated from the main group. When comparing the two data sets, the low ductile and the high ductile data sets, we found that the low ductility in the material did not considerably weaken the bearing strength of the bolted connections. That conclusion can also be made for the sheet shear strength as shown in Figure 5.5. The low ductile steel tests (30 mil and 39 mil) present a good agreement with the current NASPEC predictions which was originally developed for high ductile steel connections. As mentioned earlier, the proposed bearing strength method and the current NASPEC (2007) sheet shear strength method can be used for low ductile steel. The effect of material ductility was obvious on the hole deformation. In fact, it was observed that when low ductile sheets were used, the connections had less hole elongation compared to the high ductile steel at peak loads. Accordingly, the tilt angle of the bolt in the low ductile steel connections was less than in the high ductile steel single shear connections. Figures 5.6 and 5.7 show the bearing failure of a 43 mil high ductile steel connection and the bearing failure of a 39 mil low ductile steel connection respectively. The high ductile steel sheet warped to a great extent and the elongation of the hole was large enough to allow the head of the bolt to pass through the sheet. Similarly, in the low ductile steel connections the bolt tilted and, in some tests, the bolt head and the nut went through the sheet. As a general finding, the low ductile steel sheets revealed less warping and hole deformation than the high ductile steel sheets.

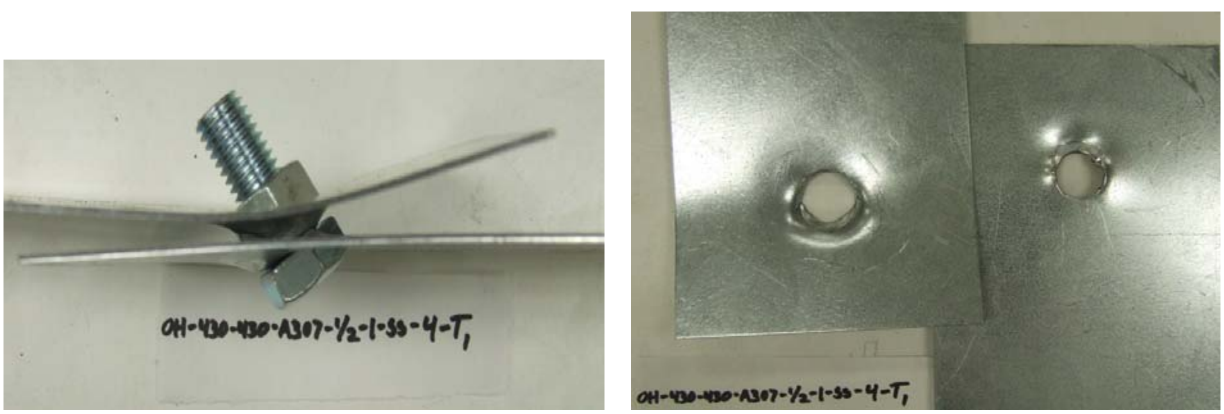


Figure 5.6- 43 mil high ductile steel bearing failure.

Figure 5.7- 39 mil low ductile steel bearing failure.

5.4. A307 vs A325 Bolts

Both A325 bolts and the A307 Type A bolts were used throughout these tests. They both have the same nominal shank diameter (1/2 in.); nevertheless, the A325 bolts have larger head and nut sizes (measured side to side dimension 0.862 in.) compared to that of the A307 Type A bolt (measured side to side value 0.739 in.). The effect of ASTM A307 Type A and A325 bolts on connections strength was investigated by the tests on 68 mil single shear connections using one ½ in. shank diameter bolt. The test results are listed in Tables 4.5 and 4.6. A comparison of the 68 mil tests with two types of bolts for bearing strength is shown in Table 5.6. The results show that connections with A325 bolt yielded rationally higher bearing strength with an average value of 18% higher than those using A307 bolts. The bolt head and nut have partial function as washers in the bolted connections. Therefore, the larger size of head and nut in A325 bolt help to having a small tilting angle of the bolt as well as the curling of the sheet. In addition, a higher bearing strength was achieved. The bearing failures of single shear connections by using A307 and A325 bolt are shown respectively in Figures 5.8 and 5.9. It can be observed that the A325 bolt ended up with less rotation than the A307 bolt. As a result, the use of A325 bolt is more valuable for bearing strength in single shear connections without washers.

Table 5.7 shows the 68 mil tests with two types of bolts for sheet shear strength. It was found that the A325 bolt connections yielded slightly higher sheet shear strength than the A307 bolt connections with an average 8% increase. The sheet shear failure mode of 68 mil single shear connections with A307 bolt and A325 bolt are illustrated respectively in Figure 5.10 and Figure 5.11. It was observed that the A307 bolt tilted to the highest degree in single shear and the sheet warped. The A325 bolt achieved typical sheet shear failure in the sheet and the bolt tilted but not as much as the A307 bolt did.

Generally, based on the results, the employ of A325 bolt could increase the bearing strength and sheet strength of single shear bolt connections due to the larger head and nut sizes compared to the A307 Type A bolt with the same nominal bolt diameter. The tests emphasize that due to the fact that the improvement is greater in the bearing strength. The proposed design method for bearing strength was calibrated by the tests on A307 bolts and was, therefore, conservative for connections using A325 bolts.

Table 5.6 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	

Figure 5.8 Bearing failure of a 68 mil single shear connection with one A307 bolt.

Figure 5.9 Bearing failure of a 68 mil single shear connection with one A325 bolt.

Table 5.7 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	

Figure 5.10 Sheet shear failure of a 68 mil single shear connection with one A307 bolt.

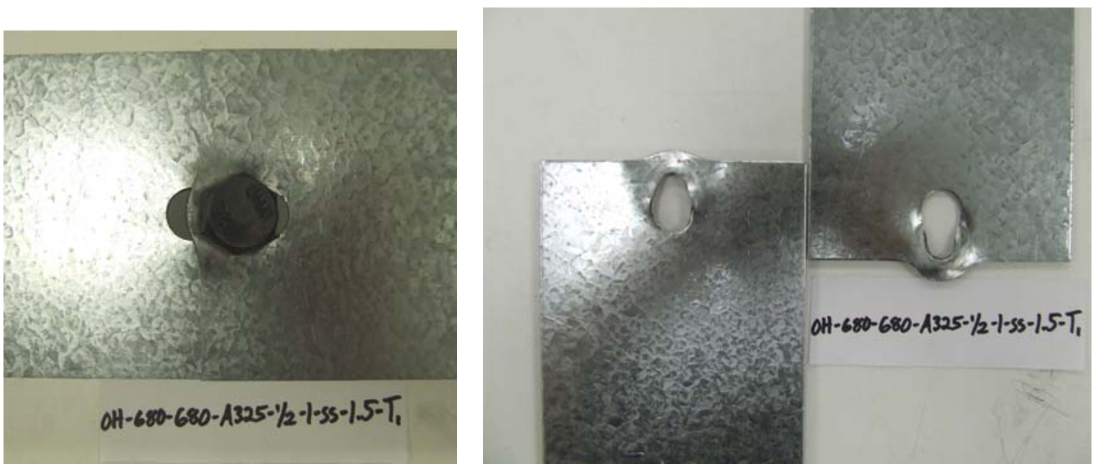


Figure 5.11 Sheet shear failure of a 68 mil single shear connection with one A325 bolt.

5.5. Connections with Different Sheets and Different Hole Sizes

Throughout this research a variety of sheet thicknesses and hole sizes were used in bolted connections tests without washer. In this section, 33 mil sheets bolted connection tests were evaluated based on four configurations. In all of the four configurations, washers were not used, single shear was employed, and single 1/2 in. A307 bolt was utilized. In the first configuration, each sheet had an oversized hole. In the second configuration, one sheet had a standard hole size while the other sheet had an oversized hole. In the third configuration, each sheet had a standard hole size. In the last configuration, a 33 mil sheet assembled with a 43 mil sheet and each of these sheets had an oversized hole.

The results of these four configurations are summarized in Table 5.8 and it indicates that the use of a standard hole on one sheet and an oversized hole on the other sheet, the second configuration, may increase the bearing strength of the connection. The use of thicker material on one sheet, the fourth configuration, can also improve the bearing strength of the connection. The enhancement in the bearing strength by using higher strength configurations in one connected sheet can be achieved; however, the increase in strength is not significant. It is recommended that the connection strength be calculated according to the thinner sheet configuration.

Table 5.8 Comparison among for 33 mil Single Shear Connections Using One 1/2 in. 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%

5.6. Two-Bolt Connections with Oversized Holes in Bearing and Shear Combined Failure

Throughout the tests, it was obvious that the shear failure most likely occurred at the hole that located close to the sheet edge, edge distance = 1.5, whereas the bearing failure occurred at the other hole, which was located at a distance equals to 3 times the nominal bolt diameter from the center of the first hole. Tables 5.9 and 5.10 give a comparison between the peak loads of the combined failure and the typical bearing failures in two-bolt connections and the typical shear failure in one-bolt connections in single shear and double shear respectively. 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 was greater than sheet shear failure and less than the bearing failure. The strength of the combined failures was closer to the shear strength due to the fact that the observed bearing strength was considerably higher than the shear strength. Due to the complexity of the load distribution between the two bolts in the specific connection configuration, further investigation should be conducted. It is recommended to use sheet strength for both bolts to predict the connection strength for this specific configuration.

Table 5.9 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 5.10 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

5.7. Options of Washers and Hole Sizes (Additional Group)

Additional group tests were conducted in order to identify the differences in bearing strength between connections having either standard on oversized holes with or without washers. The test results are shown in chapter 4, Table 4.10, where P_{NAS} is the bearing strength determined by the current NASPEC (2007) method for connections with standard holes.

The conducted tests on connections with standard holes were compared with the previous tests conducted by other researchers. Wallace, LaBoube, Schuster (2002) summarized previously conducted tests and used the data to calibrate the current NASPEC Method. Figure 5.12 illustrates a comparison between the previous tests and the tests of this research for 33 mil and 43 mil sheets with single shear connections with washers on standard holes. Apparently, the Figure shows that the tests of this research fairly match the previous data for single shear connections with washers on standard holes.

Figure 5.13 illustrates a similar comparison to Figure 5.12 but on the “without washer” option. Figure 5.13, on the other hand, addresses the connections of standard holes without washers. The Figure indicates that the tests of this research on connections without washers on standard holes locate at the bottom of the previous test data pool; however, the test data do not exceed the boundary limits.

By comparing the additional group and the main group tests on the 33 mil and 43 mil single shear connections, we found that the connections with oversized holes yield less bearing strength than those with standard holes whether washers were used or not. The ratios of bearing strength of connections with oversized holes to connections with standard holes are listed in Table 5.11. The reduction, therefore, in the bearing strength could be as large as 20% for single shear connections.

Table 5.11 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

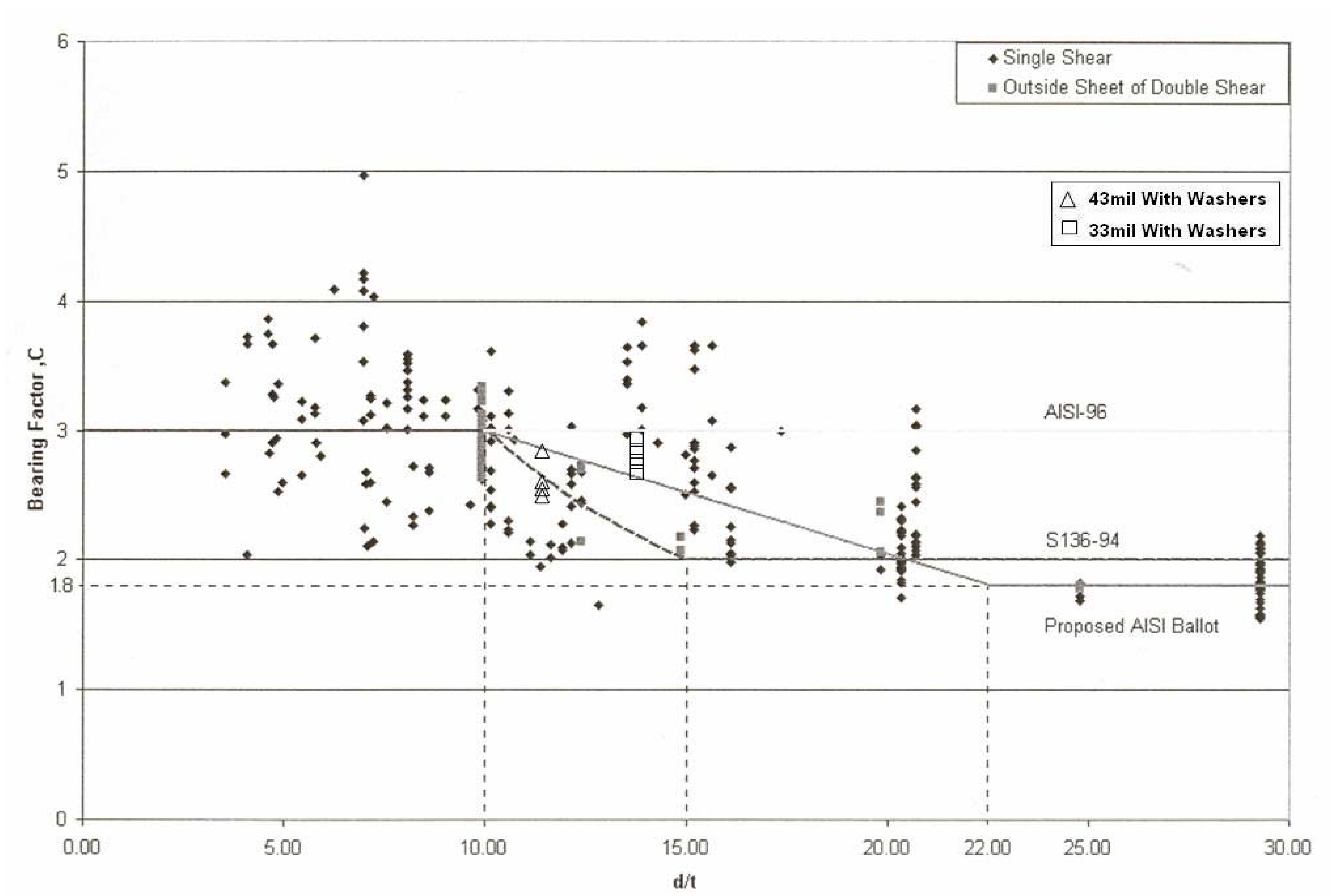


Figure 5.12 Bearing factor C for single shear and outside sheets of double shear bolted connections [with washers]. (Wallace, LaBoube, Schuster, 2002)

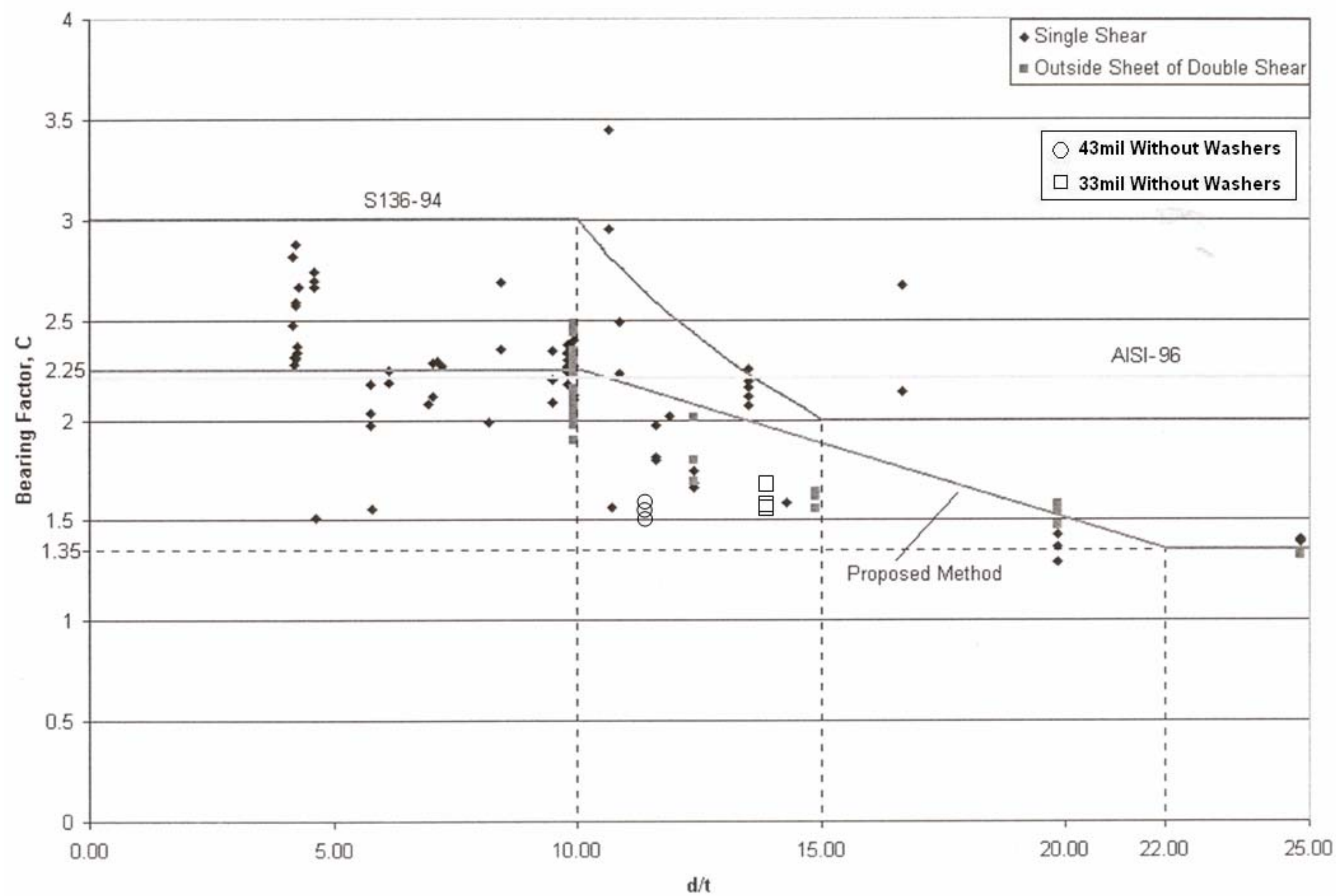


Figure 5.13 Bearing factor C for single shear and outside sheets of double shear bolted connections [without washers]. (Wallace, LaBoube, Schuster, 2001)

5.8. Sheet Bearing Strength of Bolted Connections Without Washers on Short Slotted Holes

In this section, we compared the test results of the conducted connections with short slotted holes with the connections with oversized holes. Also, we examined the predictions by both design methods; the current NASPEC (2007) method and the new design method proposed in this report. The test-to-predicted ratios "P_{test}/P_{NAS}" are listed in chapter 4, Tables 4.11 and 4.12, where P_{test} is the peak load per bolt and P_{NAS} is the NASPEC (2007) prediction for the bearing strength of single shear without washers for the thinner sheet.

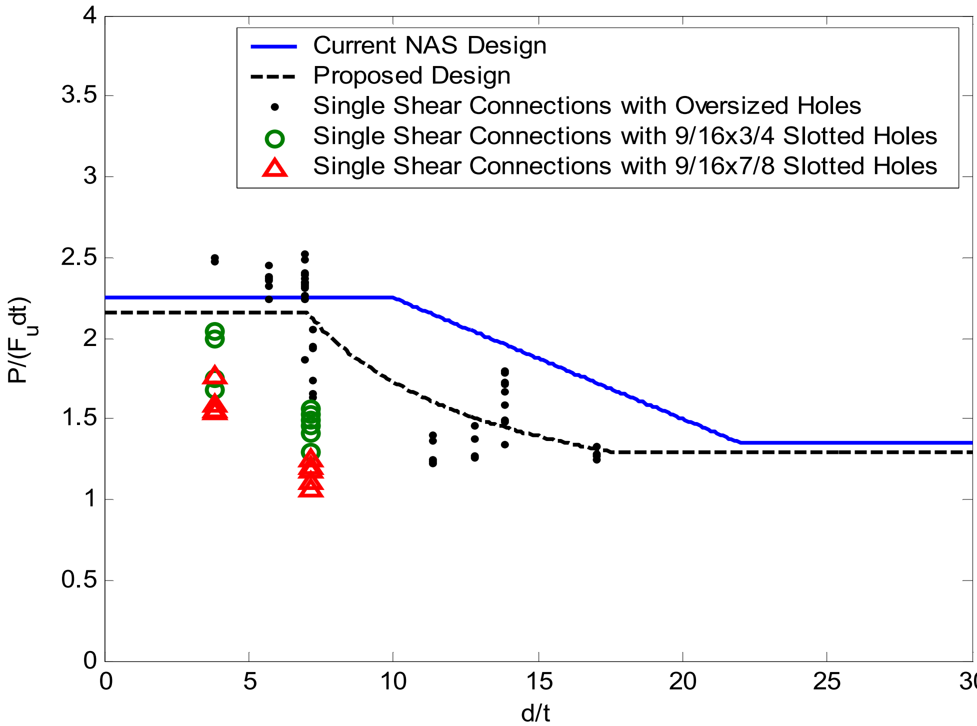


Figure 5.14 Test results vs. design methods for single shear connections in bearing.

An evaluation, in terms of the bearing strength, of the test results with the design methods is shown in Figure 5.14. The figure points out that a low bearing strength was achieved when single shear connections were used with two different short slotted holes comparing to the same connection configuration on oversized holes. The average test-to-NASPEC prediction ratio for the single shear connections with 9/16 in.×3/4 in. slots is 0.72, whereas for the single shear connections with 9/16 in.×7/8 in. slots, the ratio is 0.60. The reduction in bearing strength was due to the fact that the short slotted holes were wider than the oversized holes; thus, it made it easier for the bolt head and nut to rotate and went through the sheets. It is recommended that, for single shear connections, when either 9/16 in.× 3/4 in. or 9/16 in.× 7/8 in. short slotted holes was used, washers must be utilized.

The tilting of bolt was almost prevented throughout the double shear connection tests. The configuration with double shear resulted in an increase in the bearing strength. A comparison between the test results and the design methods for the bearing strength of inside sheet of double shear connections is shown in Figure 5.15. It was found that the double shear connections with short slotted holes had 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 in.×3/4 in. slots is 0.99 with a standard deviation of 0.163, whereas for the double shear connections with 9/16 in.×7/8 in. slots, the average ratio is 0.96 with a standard deviation of 0.149. It is recommended that the newly proposed design method be used for the inside sheet of a double shear bolted connection with 9/16 in.×3/4 in. or 9/16 in.×7/8 in. slotted holes. The ratios of test-to-NASPEC prediction of the new design method (P_{test}/P_{NEW}) are listed in chapter 4, Tables 4.13 and 4.14.

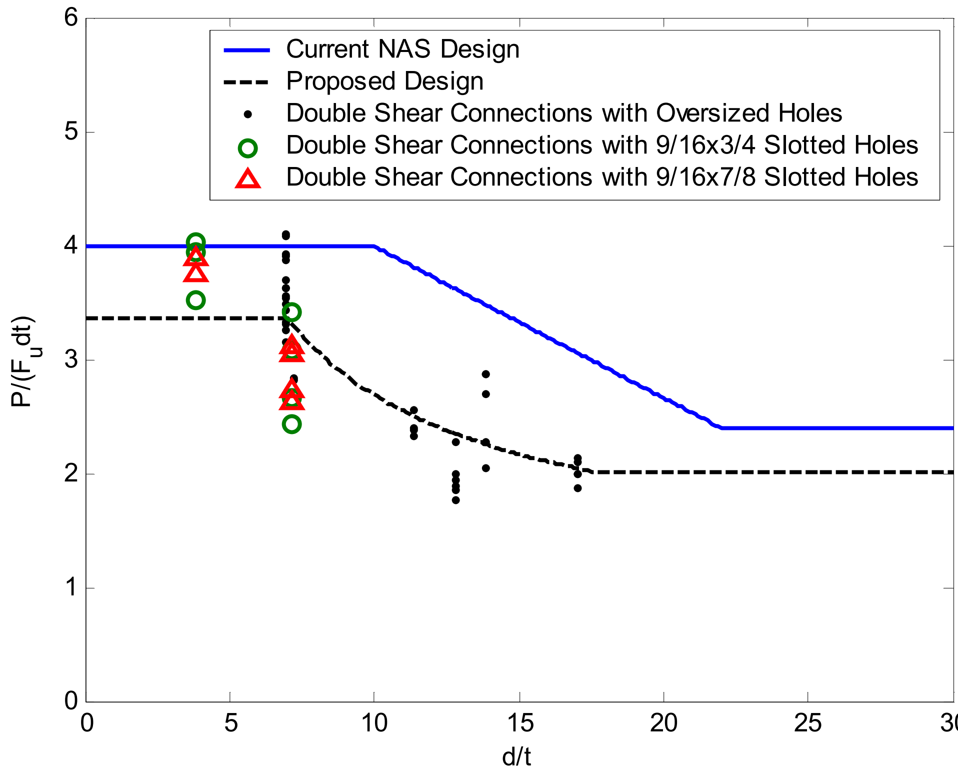


Figure 5.15 Test results vs. design methods for double shear connections in bearing.

5.9. Sheet Shear Strength of Bolted Connections Without Washers on Short Slotted Holes

A comparison was conducted by using the test results with the NASPEC prediction for shear strength of bolted connections on standard holes. The test-to-NASPEC prediction ratios are listed in Chapter 4, Tables 4.15 and 4.16. Because the bolt had a large tilting angle in the single shear connections on short slotted holes, the tested shear strength was systemically lower than the NASPEC predictions.

On the other hand, the tilting of the bolt was prevented to some extent so that a typical shear failure was achieved and the connection strength was significantly improved in the double shear tests. The peak loads of the double shear tests had a good agreement with the NASPEC prediction, the average test-to-predicted ratio is 1.03 with a standard deviation of 0.037. A comparison between the test results and the

NASPEC prediction is shown in Figure 5.16. It is recommended that the current NASPEC prediction for sheet shear strength be used for double shear connections using 9/16 in. × 3/4 in. and 9/16 in. × 7/8 in. slotted holes. It is also recommended that washers be required for single shear connections with slotted holes in shear.

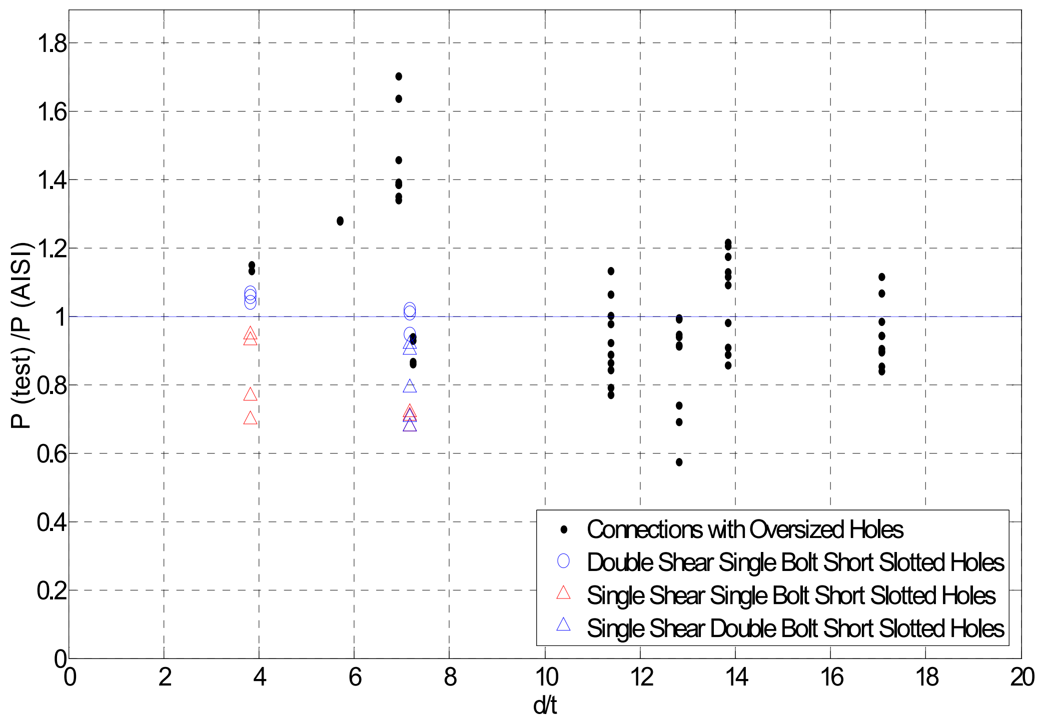


Figure 5.16 Test results of oversized holes vs. sheet shear strength of short slotted holes.

5.10. Two-Bolt Connections with Short Slotted Holes in Bearing and Shear Combined Failure

Throughout the tests, a combined failure mode, the bearing and the shear, was occurred on the connections with double bolts and e/d = 1.5. The configuration was observed on 68 mil connections and the results are summarized in Chapter 4, Table 4.17. A comparison between the combined failures with the other two typical failure modes is illustrated in Table 5.12. P_{test} in Table 5.12 is the average peak load per bolt. It was found that the strength of the combined failure modes is close to sheer failure. We can predict the strength of the specific configuration by assuming both bolts fail in the sheet shear failure.

Table 5.12 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

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusion

In order to investigate both the sheet shear strength and bearing strength tensile tests on cold-formed steel connections without washers on oversized and short slotted holes were conducted. The tests results show that current NASPEC (2007) design provisions for the sheet shear strength can be used for the bolted connections without washers on oversized holes in both single shear and double shear configurations. Additionally, it was found throughout the tests results that the NASPEC provisions have good agreement with the double shear connections without washers on short slotted holes. However, the single shear connections without washers on short 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 show that the bolted connections without washer on oversized and short slotted holes gave lower strength than the connections with standard holes. As a result, the current NASPEC design method yielded none conservative predictions for those connections having greater holes. Based on the test results, new bearing factor C and modification factor m_f 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. It was found that the method also works well for the connections with short slotted holes in double shear. Large reduction in bearing strength was observed on the single shear connections with short 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 equally 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.

6.2. Future Work

The future work will focus on the study of the fracture failure, Type III failure, for the bolted connections without washers for oversized and short slotted holes, and the results will be examined and compared to NASPEC 2007 Section E3.2. The performance of the two grades of bolts, A307 and A325, in the Type III failures will be investigated. Additionally, the behavior of the low ductile steel and the high ductile steel in the Type III failures will be studied.

REFERENCES

American Institute of Steel Construction (AISC). (2005). *Specification for Structural Steel Buildings.* Chicago, IL: Author.

American Society for Testing and Materials (ASTM). (2004). *E8/E8M-08 Standard Test Methods for Tension Testing of Metallic Materials*. Chicago, IL: Author.

Chong, KP and Matlock, RB. (1975). Light-gage steel bolted connections without washers. *Journal of the Structural Division, 101*.

Gilchrist, RT and Chong, KP. (1979). Thin light-gage bolted connection without washers. *Journal of the Structural Division, 105*.

Hsiao, L, Yu, WW and Galambos, TV. (1990). AISI LRFD method for cold-formed steel structural members. *Journal of Structural Engineering, 116*(2), 500-517.

Hsiao, L, Yu, WW and Galambos, TV. (1998). *Load and Resistance Factor Design of Cold Formed Steel, Calibration of the AISI Design Provisions*. Ninth Progress Report, Civil Engineering Study 88-2, University of Missouri-Rolla.

Ip, KH and Chung, KF. (1999). Failure modes of bolted cold-formed steel connections under static shear loading advances in steel structures. ICASS '99 (pp. 269-276).

Kim, TS, Han, BS and Shin, SW. (2001). *Prediction of ultimate behavior of bolted connections in cold-formed stainless steel using numerical analysis*. Ansan, Korea: Sustainable Building Research Center, Hanyang University.

LaBoube, RA. (1988). *Strength of bolted connections: Is it bearing or net section?* Ninth International Specialty Conference on Cold–Formed Steel Structures, St. Louis, MO.

LaBoube, RA. (1995). *Serviceability limit state for cold-formed steel bolted connections*. Third International Workshop on Connections in Steel Structures, University of Trento, Trento, Italy, May 1995.

LaBoube, RA and Yu, WW. (1995). *Tensile and bearing capacities of bolted connections*. Final Summary Report, Civil Engineering Study 95-6, Cold-Formed steel Series, Department of Civil Engineering, University of Missouri-Rolla.

LaBoube, RA and Yu, WW. (1996). *Additional design considerations for bolted connections*. Proceeding of the 13th International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla.

Lim, JBP and Nethercot, DA. (2003a). *Ultimate strength of bolted moment-connections between cold-formed steel members*. Silwood Park, Ascot, Berkshire, United Kingdom: The Steel Construction Institute.

Lim, JBP and Nethercot, DA. (2003b). *Stiffness prediction for bolted moment connections between cold-formed steel members*. Silwood Park, Ascot, Berkshire, United Kingdom: The Steel Construction Institute.

Maggia, YI, Gonçalvesa, RM, Leonb, RT and Ribeiroc, LFL. (2005). Parametric analysis of steel bolted end plate connections using finite element modeling. *Journal of Constructional Steel Research, 61*, 689-708.

NASPEC. (2007). *North American specification for the design of cold-formed steel structural members* (2007 ed.). Washington, DC: American Iron and Steel Institute.

Puthli, R and Fleischer, O. (2001). Investigations on bolted connections for high strength steel members. *Journal of Constructional Steel Research, 57*, 313-326

Research Council on Structural Connections (RCSC). (2004). *Specification for structural joints using ASTM A325 or A490 bolts*. Chicago, IL: Author.

Rogers, CA and Hancock, GJ. (1998a). Bolted connection tests for thin G550 and G300 sheet steels. *Journal of Structural Engineering*, 798-808.

Rogers, CA and Hancock, GJ. (1998b). *New bolted connection design formulae for G550 and G300 steels less than 1.0 mm thick*. Research Report No. R769, Department of Civil Engineering, Centre for Advanced Structural Engineering, University of Sydney, Sidney, Australia, June 1998.

Rogers, CA and Hancock, GJ. (1999). Bolted connection design for sheet steels less than 1.0 mm thick. *Journal of Constructional Steel Research, 51*(2), 123-146.

Rogers, CA and Hancock, GJ. (2000). Failure modes of bolted sheet steel connections loaded in shear. *Journal of Structural Engineering, 126*(3), 288-296.

Seleim, S and LaBoube, R. (1996). Behavior of low ductility steels in cold-formed steel connections. *Journal of Thin-Walled Structures, 25*(2), 135-151.

Wallace, JA and Schuster, RM. (2002). *Testing of bolted cold-formed steel connections in bearing (with and without washers)*. Proceedings of the 16th International Specialty Conference on Cold-Formed Steel Structures, Orlando, FL.

Wallace, JA, Schuster, RM and LaBoube, RA. (2001a). *Calibrations of bolted cold-formed steel connections in bearing (with and without washers).* Final report. Washington, DC: American Iron and Steel Institute.

Wallace, JA, Schuster, RM and LaBoube, RA. (2001b). *Testing of bolted cold-formed steel connections in bearing (with and without washers)*. Final report RP-1-4, Washington, DC: American Iron and Steel Institute.

Winter, G. (1956a). Tests on bolted connections in light gage steel. *Journal of the Structural Division, 82*, 513-528.

Winter, G. (1956b). *Light gage steel connections with high-strength, high torqued bolts*. International Association for Bridge and Structural Engineering, vol. 16.

Yu, C. (2005). *Distortional buckling of cold-formed steel members in bending*. PhD dissertation. Johns Hopkins University, Baltimore, MD.

Yu, WW. (1982). *AISI design criteria for bolted connections*. Proceeding of the 6th International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla.

Zadanfarrokh, F and Bryan, ER. (1992). *Testing and design of bolted connections in cold formed steel sections*. Proceedings of Eleventh International Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri.