

# **Strength and Reliability of Bolted Connections Susceptible to Tearout**

**A Thesis Presented for the  
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**Nicolo Franceschetti  
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## ABSTRACT

The limit state of tearout can complicate the design of steel bolted connections since, in contrast to the limit states of bearing and bolt shear rupture, tearout strength can vary from bolt to bolt within a connection. Under the current AISC *Specification*, tearout strength is proportional to the clear distance, in the direction of force, between the edge of the hole and the edge of the adjacent hole or edge of the material. However, recent studies have suggested that the use of clear distance may not accurately represent tearout strength and have proposed alternative lengths for use in strength equations. A reevaluation of the limit state of tearout is presented in this work, including a thorough evaluation of the proposed alternative tearout lengths using a large database of previously published experimental work and new experiments with various edge distances and hole types. Equations with the alternative tearout lengths were found to be more accurate than those with clear distance, especially for small edge distances. Design recommendations including the alternative tearout lengths were developed. A reliability study on the existing provisions and recommended provisions was also completed to ensure the safety of these recommendations. In addition, an alternative design approach was developed in which the limit state of tearout is captured implicitly through reduction factors applied to the bearing and shear rupture strength. The results of this work increase understanding of the limit state of tearout and offer improved methods of evaluating this limit state in design.

## TABLE OF CONTENTS

|                                                           |    |
|-----------------------------------------------------------|----|
| CHAPTER I: INTRODUCTION.....                              | 1  |
| Overview .....                                            | 1  |
| Theory of Bearing and Tearout.....                        | 2  |
| History of Provisions .....                               | 6  |
| Current Standards.....                                    | 13 |
| Objective and Scope of Research .....                     | 14 |
| Objectives .....                                          | 15 |
| Scope and Outline .....                                   | 15 |
| CHAPTER II: LITERATURE REVIEW .....                       | 17 |
| Overview .....                                            | 17 |
| Creation of Experimental Database .....                   | 17 |
| Overview .....                                            | 17 |
| Criteria for Database .....                               | 18 |
| Concentrically Loaded Connections .....                   | 20 |
| Overview .....                                            | 20 |
| Additional Criteria .....                                 | 20 |
| Database Characteristics .....                            | 22 |
| Eccentrically Loaded Connections .....                    | 27 |
| Review of Database Specimens .....                        | 28 |
| Review of Single and Double Angle Bolted Connections..... | 33 |
| Summary .....                                             | 34 |
| Alternative Tearout Lengths .....                         | 36 |
| CHAPTER III: EVALUATION OF PUBLISHED EXPERIMENTS.....     | 39 |
| Overview .....                                            | 39 |
| Strength of Single-Bolt Specimens .....                   | 39 |
| Strength of Multiple-Bolt Specimens .....                 | 45 |
| Effects of Bolt Tightening .....                          | 50 |
| Mixed Failures .....                                      | 51 |
| CHAPTER IV: EXPERIMENTAL TESTS.....                       | 55 |
| Overview .....                                            | 55 |
| Test Matrix.....                                          | 55 |
| Materials and Test Setup.....                             | 56 |
| Results.....                                              | 60 |
| Failure Mechanisms .....                                  | 60 |
| Strength Evaluation.....                                  | 63 |
| Effect of Bolt Tightening.....                            | 65 |
| CHAPTER V: RELIABILITY ANALYSIS.....                      | 67 |
| Overview .....                                            | 67 |
| Methodology .....                                         | 67 |
| Statistical Parameters .....                              | 71 |
| Variable Sensitivity Analysis.....                        | 74 |
| Reliability Analysis and Results .....                    | 77 |

|                                               |    |
|-----------------------------------------------|----|
| CHAPTER VI: ALTERNATIVE DESIGN APPROACH ..... | 82 |
| Overview .....                                | 82 |
| Derivation of the Approach .....              | 82 |
| CONCLUSIONS & RECOMMENDATIONS .....           | 88 |
| REFERENCES .....                              | 91 |
| VITA .....                                    | 96 |

## LIST OF TABLES

|                                                                                                                                                                                                                                                                          |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1: Specimen Count in the Database .....                                                                                                                                                                                                                            | 19 |
| Table 2: Summary of Experimental Data Sources.....                                                                                                                                                                                                                       | 21 |
| Table 3: Summary of Basic Eccentrically Loaded Bolt Groups.....                                                                                                                                                                                                          | 31 |
| Table 4: Summary of Single Plate Shear Connections .....                                                                                                                                                                                                                 | 32 |
| Table 5: Test-to-Predicted Ratio Statistics for Various Evaluations of the Load at 1/4 in.<br>Deformation for Single-Bolt Specimens (data from 223 specimens, data from 192<br>specimens meeting minimum edge distance requirements in parentheses).....                 | 41 |
| Table 6: Test-to-Predicted Ratio Statistics for Various Evaluations of Ultimate Load for<br>Single-Bolt Specimens (data from 301 specimens, data from 234 specimens meeting<br>minimum edge distance requirements in parentheses) .....                                  | 41 |
| Table 7: Test-to-Predicted Ratio Statistics for Various Evaluations of the Load at 1/4 in.<br>Deformation for Multiple-Bolt Specimens (data from 100 specimens, data from 62<br>specimens meeting minimum edge distance and spacing requirements in<br>parentheses)..... | 48 |
| Table 8: Test-to-Predicted Ratio Statistics for Various Evaluations of Ultimate Load for<br>Multiple-Bolt Specimens (data from 136 specimens, data from 48 specimens<br>meeting minimum edge distance and spacing requirements in parentheses) .....                     | 48 |
| Table 9: Mean values of test-to-predicted ratios based on level of tightening .....                                                                                                                                                                                      | 52 |
| Table 10: Analysis of specimens tested by Cai and Driver (2008) that exhibited mixed<br>failures.....                                                                                                                                                                    | 54 |
| Table 11: Experimental Testing Summary .....                                                                                                                                                                                                                             | 57 |
| Table 12: Mean Test-to-Predicted Ratio at the 1/4 in. Deformation Limit State .....                                                                                                                                                                                      | 64 |
| Table 13: Mean Test-to-Predicted Ratio at the Ultimate Limit State .....                                                                                                                                                                                                 | 64 |
| Table 14: Summary of Statistical Parameters .....                                                                                                                                                                                                                        | 73 |
| Table 15: Sensitivity of Bolt Diameter and Live-to-Dead Load Ratio on Reliability .....                                                                                                                                                                                  | 76 |
| Table 16: Ratio of tearout strength to bearing strength for edge bolts .....                                                                                                                                                                                             | 83 |
| Table 17: Ratio of tearout strength to bearing strength for interior bolts .....                                                                                                                                                                                         | 83 |

## LIST OF FIGURES

|                                                                                                                              |    |
|------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1: Comparison of Bearing and Tearout Mechanisms (Segui 2013) .....                                                    | 3  |
| Figure 2: Load-Deformation Plots of Varying Edge Distances (Wang et al. 2017).....                                           | 5  |
| Figure 3: Common Failure Modes of Concentrically Loaded Bolted Connections .....                                             | 7  |
| Figure 4: Experimental Data and Lines of Fit for Normalized Edge Distance vs. Bearing<br>Ratio (Fisher and Struik 1974)..... | 10 |
| Figure 5: Bearing Strength per 1993 Specification Showing Discontinuity (Carter et al.<br>1997) .....                        | 12 |
| Figure 6: Bolt Tightness.....                                                                                                | 23 |
| Figure 7: Failure Modes.....                                                                                                 | 23 |
| Figure 8: Plate Yield Strength.....                                                                                          | 24 |
| Figure 9: Plate Ultimate Strength .....                                                                                      | 24 |
| Figure 10: Plate Thickness.....                                                                                              | 25 |
| Figure 11: Normalized Edge Distance .....                                                                                    | 25 |
| Figure 12: Bolt Diameter .....                                                                                               | 26 |
| Figure 13: Number of Bolts .....                                                                                             | 26 |
| Figure 14: Eccentrically Loaded Shear Connection Set-Up (Crawford and Kulak 1971)                                            | 29 |
| Figure 15: Tests by Franchuk et al. showing tearout of the bottom bolt and bolt tilting..                                    | 35 |
| Figure 16: Tearout Length Comparison.....                                                                                    | 37 |
| Figure 17: Normalized Strength Comparisons Between Tearout Lengths for Ultimate<br>Load .....                                | 43 |
| Figure 18: Normalized Strength Comparisons Between Tearout Lengths for Ultimate<br>Load .....                                | 44 |
| Figure 19: Ratio of Ultimate Load and 1/4 in. Deformation versus Normalized Clear<br>Distance.....                           | 46 |
| Figure 20: Test-to-Predicted Ratio Excluding Tearout versus Normalized Clear Distance<br>.....                               | 49 |
| Figure 21: Experimental Test Setup .....                                                                                     | 59 |
| Figure 22: Load-Deformation Curves for Experimental Tests .....                                                              | 61 |
| Figure 23: Photograph of specimen OVS2 after testing .....                                                                   | 62 |
| Figure 24: Photograph of specimen OVS3 after testing .....                                                                   | 62 |
| Figure 25: Test-to-Predicted Ratios at Ultimate Limit State with Best Fit Lines.....                                         | 66 |
| Figure 26: Snug-Tightened Specimen versus Untightened and Greased Specimen.....                                              | 66 |
| Figure 27: Reliability at Minimum Edge Distance and Spacing .....                                                            | 79 |
| Figure 28: Reliability at Typical Edge Distance and Spacing .....                                                            | 80 |
| Figure 29: Reliability at Maximum Edge Distance and Spacing.....                                                             | 81 |
| Figure 30: Example Connection for the Alternative Design Method .....                                                        | 85 |

# CHAPTER I: INTRODUCTION

## Overview

Bolted connections are widely used in steel structures for their constructability and structural reliability. Several limit states apply to bolted connections, and both the bolts and connected material must be evaluated. In a bearing-type shear connection, load is transferred through the fasteners in shear into the connected material in bearing. Based on theory and experimental testing, provisions and design equations were adopted that could estimate the strength of a bearing-type connection. Under the current *AISC Specification* (AISC 2016), the effective strength of a fastener in a bearing-type bolted steel connection is equal to the minimum strength computed for the limit states of bolt shear rupture, bearing, and tearout. By this method, it is possible, for example, to have the strength of a bolt group controlled by a combination of tearout for the bolts near an edge and bolt shear rupture for the remaining bolts. The possibility of this interaction of limit states is in contrast to a common practice where bolt shear rupture is treated as independent from bearing and tearout (e.g., Salmon et al. 2009). Evaluating the potential interaction of bolt shear rupture, bearing, and tearout complicates the design of bolt groups, primarily because the strength of an individual bolt for the limit state of tearout can vary from bolt to bolt within a group. Given the increased complexity and recently proposed alternative strength equations (Clements and Teh 2013; Kamtekar 2012), a reevaluation of the limit state of tearout is warranted to determine if changes can be made that lead to more accurate and efficient connection designs.

## Theory of Bearing and Tearout

For bolts sufficiently far from edges of material and adjacent bolts, the strength of the connected material near the bolt is controlled by bearing. The limit state of bearing is characterized by plastic deformations of the connected material near the bolt hole and a long yield plateau in the load-deformation relationship. However, the connected material eventually ruptures with continued loading. In experimental testing, the peak load has been noted to occur upon reaching yield, prior to rupture or somewhere in between. However, once the yield plateau is reached, the variation in load is small.

Bearing strength has been observed to depend on the diameter of the bolt, thickness of the connected material, and the tensile strength of the connected material. The edge distance, when large, does not impact bearing strength. A bearing failure can be described as a function of the plate's area directly in front of the bolt and its ultimate bearing capacity, as shown in Eq. (1).

$$P = dt\sigma_b \quad (1)$$

where  $P$  is the failure load,  $d$  is the diameter of the bolt,  $t$  is the thickness of the connected material, and  $\sigma_b$  is the ultimate bearing stress of the connected material, or the bearing stress at a desired deformation. In research and practice,  $\sigma_b$  is determined in terms of  $F_u$  (ultimate tensile capacity of the material) multiplied by an empirically derived coefficient. In this theory, bearing stress is assumed to be uniform over the diameter of the bolt shank.

The primary limit state for connected material with smaller edge distance is tearout. Tearout is characterized by the rupture of the connected material on either side of the bolt, depicted in Figure 1. A tearout failure would occur when the two shear planes extending from the bolt hole to the nearest edge reach their ultimate shear capacity, as described

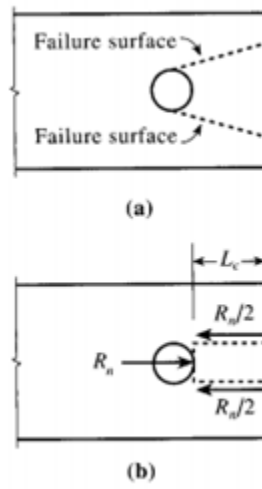


Figure 1: Comparison of Bearing and Tearout Mechanisms (Segui 2013)

in Eq. (2).

$$P = 2l_s t \sigma_s \quad (2)$$

where  $P$  is the failure load,  $l_s$  is the shearing length to the nearest edge (plate edge or bolt hole),  $t$  is the thickness of the connected material, and  $\sigma_s$  is the rupture shear stress of the connected material. The rupture shear stress is commonly taken as  $0.6F_u$  as was determined for block shear (Birkemoe and Gilmer 1978). However, other coefficients have been proposed through testing. The shear length is most often based on edge distance from either the edge or center of the bolt hole. Other shear lengths have been proposed and will be evaluated in this project.

Figure 2 demonstrates the load-deformation curves of specimens of varying edge distance tested by Wang et al. (2017). The second number in the specimen label indicates the edge distance. SD-10-30 had a nominal edge distance of 1.0 in., whereas SD-25-30 had a nominal edge distance of 2.5 in. Specimen SD-25-30 was the only bearing-controlled specimen per the *Specification* (AISC 2016). The failed specimens all show a tearout shear rupture of the connected material. However, the bearing-controlled specimen had much larger deformations. The figure depicts the decrease in capacity as the edge distance is reduced.

A similar failure mode is splitting, which involves a tensile fracture initiating at the end of the connected material. The limit state of splitting is distinct from the limit state of tearout. Equations have been proposed to predict splitting strength (Duerr 2006) and some standards treat tearout and splitting separately (e.g., ASME 2017). However, splitting is not recognized within the AISC *Specification* (AISC 2016). Therefore, equations for the

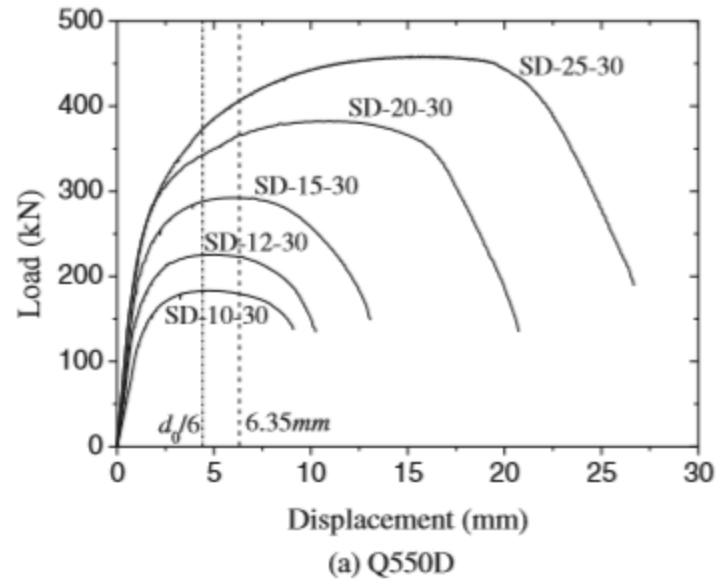


Figure 2: Load-Deformation Plots of Varying Edge Distances (Wang et al. 2017)

limit state of tearout are implicitly covering splitting as well. This approach is justified since experimental results have shown the two limit states to have similar strengths. Specimens tested by Cai and Driver (2008) show deformations and/or fracturing along the shear planes. Based on this evidence, Cai and Driver reasoned that shear planes develop their full capacity despite the presence of the splitting failure. A summary of failure modes in concentrically loaded bolted connections is provided in Figure 3. Some experiments have also shown modes of failure for bolted connections that include out-of-plane curling of unconfined plates.

Another important characterization of bolted connections is loading location. Concentrically loaded connections refer to connections loaded in line with the centroid of the bolt group. Connections where loading is not applied in line with the centroid of the bolt group are described as eccentrically loaded. Some eccentricity is present in most shear connections, such as single plate and angle connections. Eccentricity in the loading can cause additional forces on the bolts and connected material. Several methods to account for eccentricity exist, although the application of these methods to bearing and tearout have not been extensively studied (Man et al. 2006).

### **History of Provisions**

This section will provide a history of bearing and tearout as they relate to the AISC *Specification*. The changes to the provisions in the *Specification* over time are a key motivation of this research. Bearing of fasteners has been a consideration in the AISC *Specifications* since the first edition published in 1923 (AISC 1923). However, tearout was not considered beyond the minimum edge distance requirements for construction tolerance.

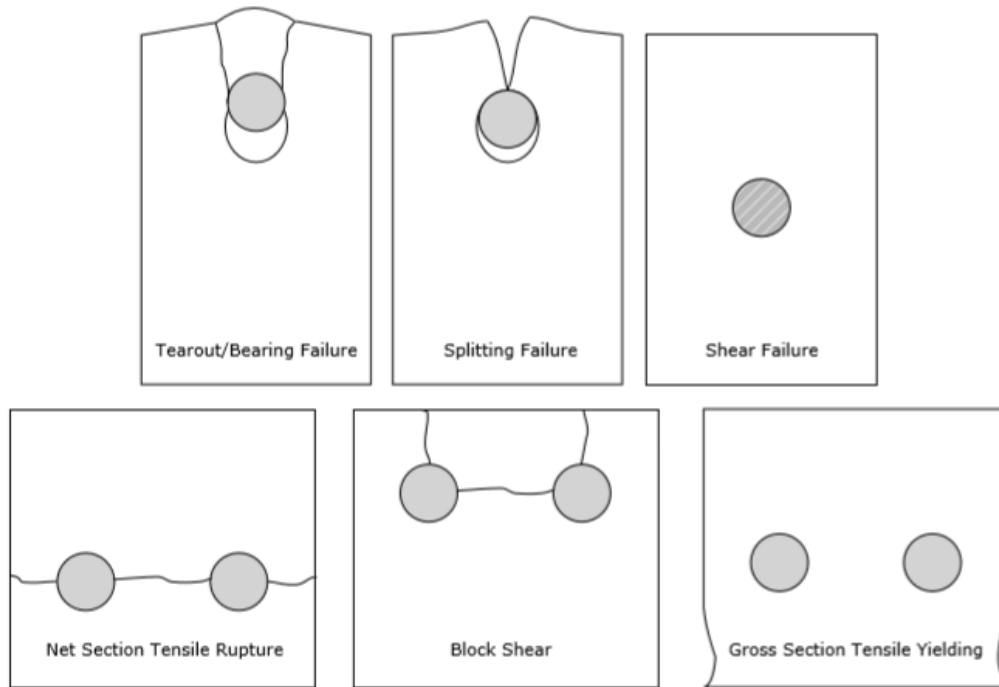


*Figure 3: Common Failure Modes of Concentrically Loaded Bolted Connections*

The appendix of the 1936 *Specification* (AISC 1936) describes a series of tension testing of riveted connections that revealed a tearout failure in the thinnest plate. The Specification reflected this finding by including a provision that the edge distance and/or spacing of a rivet be greater than the shearing area of the rivet divided by the plate thickness. This is significantly different from the modern tearout limit state because it is a function of geometry rather than stresses. The 1936 *Specification* made an exception for the case of more than three rivets in the line of stress. The appendix justifies this as the following: “Had the specimens contained several rivets in line, this [tearout] should not have occurred, as the yielding of the end of the bar would no doubt have thrown more load back onto the interior rivets.” The idea that tearout of the edge bolt can be precluded in the case of multiple bolts is revisited in later *Specifications*.

The creation of the Research Council on Riveted and Bolted Connections in 1947 led to several research projects regarding bolted connections. One outcome was an increase in the allowable bearing stress in the 1961 *Specification* (AISC 1961). The research completed by the Research Council was compiled in the *Guide to Design Criteria for Bolted and Riveted Joints* (Fisher and Struik 1974). Along with introducing LRFD design to bolted connections, tearout was reassessed using data gathered from many tests that had been completed. Two equations were suggested in the *Guide*, which were plotted as shown in Figure 4. The solid line is equivalent to Eq. (3), which is derived from the theory presented in Eq. (2).

$$P = (2t) \left( L_e - \frac{d}{2} \right) (0.7F_u) \quad (3)$$

where  $P$  is the failure load,  $t$  is the thickness of the connected material,  $L_e$  is the edge distance from the center of the bolt,  $F_u$  is the ultimate tensile strength of the connected material, and  $d$  is the diameter of the bolt. The dashed line was a simpler equation that was found to fit the data well. This equation was included in the *AISC Specification* (1978), rearranged in terms of load as shown in Eq. (4).

$$P = L_e t F_u \quad (4)$$

This was the first provision that considered the reduction of allowable stress at smaller edge distances. The exception of the edge distance check for multiple bolts in a line that existed since 1936 was removed with the justification that “critical bearing stress is significantly affected by reduction of the edge distance, even with three fasteners in line” (AISC 1978).

Frank and Yura (1981) identified that a connection with a bolt hole deformation of 0.25 in. has likely achieved much of the maximum capacity, and further loading may limit the effectiveness of the connections due to increasing deformation. Through experimental data, they determined a stress that would limit the deformation to 0.25 in., shown in Eq. (5).

$$\sigma_b = 2.4 F_u \quad (5)$$

Frank and Yura’s findings were directly incorporated in the 1986 *Specification* (AISC 1986). An additional condition was added to the provisions for the case where 1/4 in. deformation is tolerable, or as the *Specification* notes, “deformation around the bolt hole is not a design consideration.” This condition allowed an additional 25% higher capacity using a multiplier of 3.0 rather than 2.4. New criteria were added in which the tearout

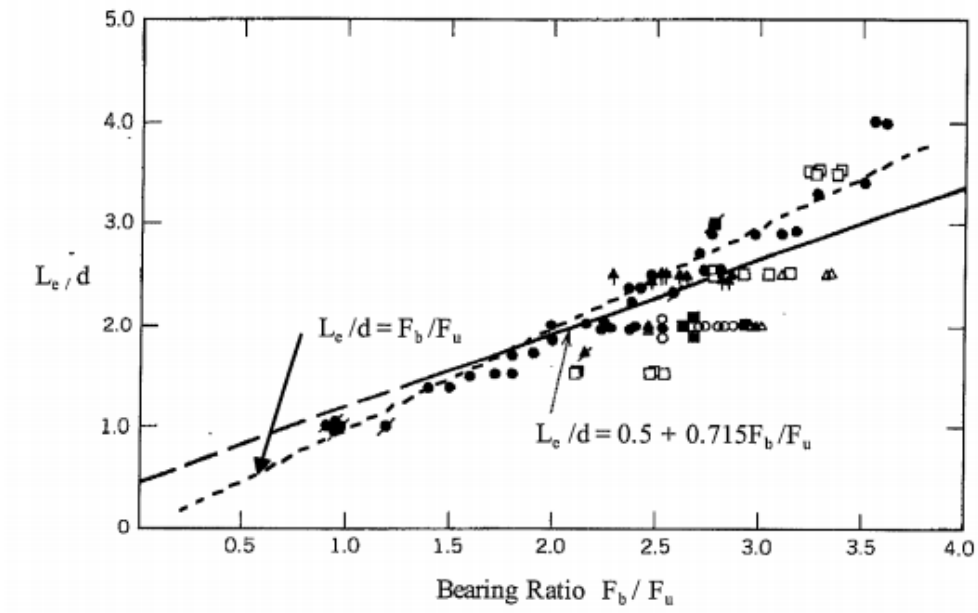


Figure 4: Experimental Data and Lines of Fit for Normalized Edge Distance vs. Bearing Ratio (Fisher and Struik 1974)

provision, Eq. (4), was not required to be checked if there were two or more bolts in a line, a minimum edge distance of  $1.5d$  was provided, a minimum spacing of  $3d$  was provided, and deformation at the bolt hole was a design consideration. These criteria were a return to previous *Specifications* that allowed an exception if several bolts were in the line of force. The exceptions were justified on the premise of load redistribution to the interior fasteners or that sufficient interior bolts in a connection would diminish the effects of reduced edge bolt hole strength if certain minimum edge distance and bolt spacing were provided.

There were no changes to the bearing and tearout provisions until the 1999 *Specification* (AISC 1999). According to Carter et al. (1997) there was a desire in the early 1990s to use clear distances to accommodate long-slotted and oversize holes without modification factors. Additionally, the existing provisions (AISC 1993) resulted in a discontinuity at an edge distance of  $1.5d$ , when the bearing strength begins controlling over tearout. This is shown in Figure 5. To achieve the desired changes, a reformulation of Eq. (3) from the *Guide* (1974), which uses clear distance, was recommended in the 1994 RCSC *Specification* (Research Council on Structural Connections 1994). The experimental tests performed by Kim and Yura (1999) and Lewis and Zwerneman (1996) verified the accuracy of the new equation and concluded that the discontinuity in the 1993 *Specification* resulted in overestimations of the strength. Afterwards, the 1999 *Specification* (AISC 1999) adopted the RCSC provisions, as shown in Eq. (6) for the case where deformation is a design consideration.

$$R_n = 1.2l_c t F_u \leq 2.4dt F_u \quad (6)$$

The equation was modified to have imply a shear strength of  $0.6F_u$  rather than  $0.7F_u$  used

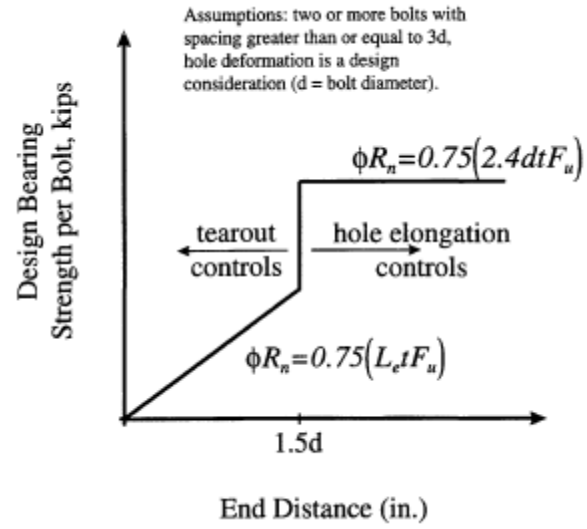


Figure 5: Bearing Strength per 1993 Specification Showing Discontinuity (Carter et al. 1997)

in Eq. (3) for consistency with the block shear rupture equations (Carter et al. 1997; Kim and Yura 1999). The provisions also removed the discontinuity at  $1.5d$  and made the check in terms of clear distance.

### Current Standards

The current standards are based on the 1999 provisions. Section J3.10 of the AISC *Specification* (2016) governs bearing and tearout strength at bolt holes. The bearing strength of a bolt in a standard, oversize, or short-slotted hole is given by Eqs. (7) and (8) (J3-6a and J3-6b in the 2016 AISC *Specification*).

$$R_n = 2.4dtF_u \quad (7)$$

$$R_n = 3.0dtF_u \quad (8)$$

where,  $R_n$  is the nominal strength,  $d$  is the bolt diameter,  $t$  is the thickness of the connected material, and  $F_u$  is the ultimate tensile stress of the connected material.

Eq. (7) is used when deformation at the bolt hole at service load is a design consideration, whereas Eq. (8) is used when deformation at the bolt hole at service load is not a design consideration. Significant bolt hole ovalization is expected to occur prior to reaching the full bearing capacity of the connected material, which may limit the effectiveness of the connection. Frank and Yura (1981) identified 1/4 in. deformation as a practical limit to define a bearing strength which also prevents excessive ovalization.

The tearout strength of a bolt in a standard, oversize, or short-slotted hole is given by Eqs. (9) and (10) (J3-6c and J3-6d in the 2016 AISC *Specification*), where the distinction between Eqs. (9) and (10) is the same as that between Eqs. (7) and (8).

$$R_n = 1.2l_c t F_u \quad (9)$$

$$R_n = 1.5l_c t F_u \quad (10)$$

where,  $l_c$  is the clear distance, in the direction of force, between the edge of the hole and the edge of the adjacent hole or edge of the material.

With the revisions over time, there has come increasing recognition of potential for interaction between bolt shear rupture, bearing, and tearout in bolt groups. User notes and commentary have been included since the 2010 *AISC Specification* (AISC 2010) to indicate that the effective strength of a bearing-type fastener is equal to the minimum strength computed for the limit states of bolt shear rupture, bearing, and tearout. The strength of a bolt group is computed from the strength of the individual fasteners. Except for special cases, neither bolt shear rupture strength nor bearing strength will vary among the individual bolts in a group. Tearout will typically vary between the edge bolt and the interior bolts. The calculation is further complicated in eccentrically loaded connections where the direction of loading for individual bolts, and consequently clear distance, is difficult to determine.

### **Objective and Scope of Research**

The purpose of this research is to further study the behavior and design methods of steel bolted connections subject to the limit states of bearing and tearout. The focus of the research is to gather and analyze experimental testing results in order to evaluate improvements that could increase accuracy or simplify the design method while maintaining reliability and safety.

## ***Objectives***

The specific objectives of the research are outlined below:

- Create a database of previous experimental tests, including eccentrically loaded connections, with an emphasis on bearing and tearout limit states
- Evaluate the accuracy of the current and alternative equations that include different tearout shear lengths and/or coefficients through the analysis of concentrically loaded experimental testing
- Perform experimental testing to fill gaps in the existing research, particularly the use of different hole types
- Evaluate the reliability of current and alternative equations
- Consider simplifications to the design procedure, including alternative design methods
- Develop recommendations for design based on the results

## ***Scope and Outline***

To achieve the above objectives, the scope of the project was developed in five stages, which form the five subsequent chapters of this thesis. Chapter II discusses the experimental database that was created in order to evaluate general trends in experimental testing and as a source of data for analysis. Also included in Chapter II is a detailed literature review of eccentrically loaded connections with a focus on the limit states of bearing and tearout. Chapter III consists of analyses of existing experimental data. The accuracy of current and alternative equations was assessed using statistical analysis of the test-to-predicted ratios, among other considerations. Chapter IV details the experimental testing of single-bolt concentrically loaded connections that investigate differing hole types

and verify the results found in the previous analyses. Chapter V includes a reliability study using Monte Carlo simulations to evaluate the safety level of the current and alternative design equations. Finally, Chapter VI introduces an alternative design approach that simplifies the design procedure through reduction factors on bearing and bolt shear rupture such that the tearout check can be precluded.

## **CHAPTER II: LITERATURE REVIEW**

### **Overview**

Due to the quantity of literature considered, the literature review was categorized in three parts. The first was a creation and evaluation of a database containing tests gathered from published research. The database was then used to perform analyses in later chapters of this thesis. The second part of the literature review encompassed a more qualitative review of some tests of interest. In particular, the eccentrically loaded connections and shear connections, that had many variations that could not be adequately described in a database. The third part of the literature review compares proposed alternative tearout shear lengths.

### **Creation of Experimental Database**

#### **Overview**

A database of experiments on steel bolted connections was developed as part of the literature review. Published papers and reports with relevant physical testing identified in the literature were collected, read, and categorized. Due to differing fields between test types, four datasets were created:

- 1) concentrically loaded lap splice connections in tension
- 2) concentrically loaded butt splice connections in tension
- 3) eccentrically loaded bolt groups
- 4) single plate bolted shear connections

Since the objectives of the research were focused on the bearing and tearout limit states, papers and reports with these failure modes were investigated if possible. However, other failures were present in the reviewed studies, mainly in the eccentrically loaded bolt

groups and single plate bolted shear connections. The number of specimens in each dataset is shown in Table 1.

### ***Criteria for Database***

To be included in the database, each specimen must 1) have obtained bearing, tearout, bolt shear rupture, or other failure strength in a physical experiment; 2) be described in a published work (preferably a peer-reviewed journal publication); and 3) be capable of being accurately described by the fields in the database. Other types of tests that were outside the scope of this project included:

- Other connections types (e.g., welded connections and moment connections)
- Connections with stainless steel, thin gage cold-formed steel, or composite materials
- Connections tested at elevated temperatures

Some specimens which had conflicting data reporting of important values were also not included. Since the analyses of the concentrically loaded connection datasets was more rigorous and included calculating predicted strengths, these connections were subject to additional criteria, which are described in the next section.

Data entered for each specimen included general information, such as author of the reference and specimen name; qualitative data, such as the bolt tightness and observed failure mode; and quantitative data, such as plate thickness and material strengths. Data was entered in original units to facilitate validation. A MATLAB script was used to read the data and convert all values to consistent units and to prepare the data for analysis performed in later chapters.

Table 1: Specimen Count in the Database

| Database Category                             | Number of Specimen | Number of Studies |
|-----------------------------------------------|--------------------|-------------------|
| Concentrically Loaded Lap Splice Connections  | 197                | 6                 |
| Concentrically Loaded Butt Splice Connections | 702                | 14                |
| Basic Eccentrically Loaded Bolt Groups        | 43                 | 4                 |
| Single Plate Bolted Shear Connections         | 42                 | 7                 |
| Total                                         | 984                | 31                |

## Concentrically Loaded Connections

### **Overview**

The purpose of the concentrically loaded connection database was to provide a source of data to complete the analyses and to reveal any gaps in existing testing. Due to their relative simplicity, numerous concentrically loaded connections have been tested as compared to eccentrically loaded connections. Concentrically loaded specimens made up 92% of the reviewed tests. 20 of the 31 of the reviewed works contained concentrically loaded connections (899 specimens). The tests completed as part of this thesis (described in Chapter IV) were considered as well. The concentrically loaded connections were subdivided into lap splices and butt splices. A lap splice refers to a connection in which two plates are fastened with one or more bolts that are subject to a single shear plane. A butt splice refers to a connection containing two exterior plates and one interior plate fastened with one or more bolts that are subject to two shear planes. These differences justified the use of separate datasets to organize the information. Table 2 provides a summary of the experimental data sources.

### **Additional Criteria**

To be included in the concentrically loaded database, either the ultimate load,  $R_{exp,u}$ , or load at 1/4 in. deformation,  $R_{exp,d}$ , must have been recorded. For specimens where  $R_{exp,d}$  was not specifically reported, but a plot of the load-deformation response of the connection was provided, the load at 1/4 in. deformation was interpolated from the plot. If the specimen reached its peak load prior to attaining 1/4 in. deformation,  $R_{exp,d}$  was set equal to the ultimate load. Accordingly,  $R_{exp,d}$  should be interpreted as a failure load at which peak strength is attained or the connection experiences 1/4 in. deformation, whichever occurs

Table 2: Summary of Experimental Data Sources

| Reference                 | Connection Type | Number of Specimens Included in Database | Number of Specimens with Bearing, Tearout, or Splitting Failures |
|---------------------------|-----------------|------------------------------------------|------------------------------------------------------------------|
| Gillett (1978)            | Lap Splice      | 54                                       | 33                                                               |
| Frank and Yura (1981)     | Butt Splice     | 16                                       | 6                                                                |
| Sarkar (1992)             | Lap Splice      | 19                                       | 2                                                                |
| Karsu (1995)              | Lap Splice      | 64                                       | 38                                                               |
| Kim & Yura (1999)         | Lap Splice      | 41                                       | 41                                                               |
| Lewis & Zwerneman (1996)  | Butt Splice     | 92                                       | 87                                                               |
| Udagawa & Yamada (1998)   | Butt Splice     | 219                                      | 47                                                               |
| Puthli & Fleischer (2001) | Butt Splice     | 25                                       | 9                                                                |
| Rex & Easterling (2003)   | Butt Splice     | 31                                       | 20                                                               |
| Udagawa & Yamada (2004)   | Butt Splice     | 42                                       | 5                                                                |
| Freitas (2005)            | Butt Splice     | 29                                       | 26                                                               |
| Brown et al. (2007)       | Butt Splice     | 94                                       | 63                                                               |
| Cai & Driver (2008)       | Butt Splice     | 44                                       | 23                                                               |
| Moze & Beg (2010)         | Butt Splice     | 38                                       | 16                                                               |
| Moze & Beg (2011)         | Butt Splice     | 24                                       | 14                                                               |
| Draganić et al. (2014)    | Lap Splice      | 9                                        | 0                                                                |
| Moze & Beg (2014)         | Butt Splice     | 19                                       | 8                                                                |
| Teh & Uz (2016)           | Lap Splice      | 10                                       | 10                                                               |
| Wang et al. (2017)        | Butt Splice     | 24                                       | 18                                                               |
| This Thesis               | Butt Splice     | 5                                        | 5                                                                |
|                           |                 | 899                                      | 471                                                              |

first. Additionally, material testing must have been conducted to determine the tensile strength,  $F_u$ , of the connected material in which failure occurred. Only specimens with standard holes were included in the database to provide consistency. A few specimens with slotted holes were identified and were evaluated separately.

### ***Database Characteristics***

In order to characterize the general trends in the tests, the variables of the datasets were plotted on histograms shown in Figure 6 to Figure 13. The most commonly tested materials were A36 and SS400 steel, explaining the distribution of yield and ultimate strengths in Figure 8 and Figure 9. However, various types of higher strength steels were prominent, including A572 Gr. 50, HQ590, and HQ780. Figure 10 shows that plate thickness was concentrated around 0.4 in. to 0.5 in. This discontinuity in plate thickness is mostly due to 219 specimens with 12 mm (0.472 in.) plates tested by Udagawa and Yamada (1998). The large majority of the specimens contained one or two bolts. Tested bolt diameters ranged from 5/8 in. to 1 in.

About half the specimens (485) did not have a valid bolt tightness as described in the AISC *Specification* (2016), which requires that bolts be at least snug-tightened. Kim & Yura (1999) justified the use of loose plates in order to achieve a lower-bound strength of the connection that does not include frictional forces. While performing tests on loose connections isolates the contribution of bearing and provides a lower bound for strength, it is potentially overly conservative to base provisions on these results. The possible effects of bolt tightening on the capacity of the connection will be described further in Chapter III and Chapter IV.

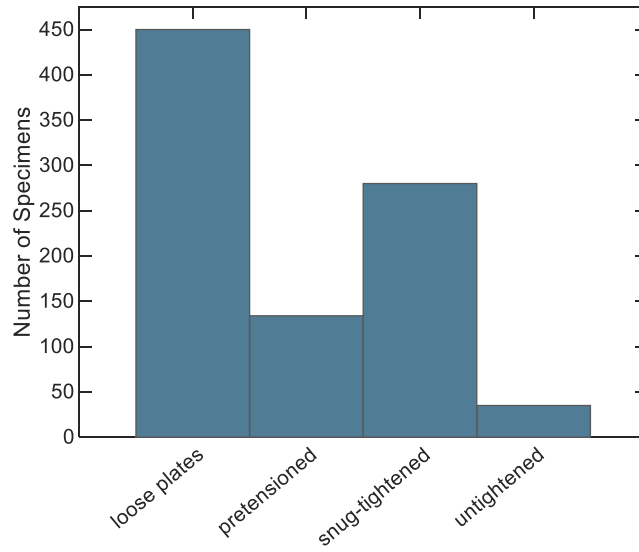


*Figure 6: Bolt Tightness*

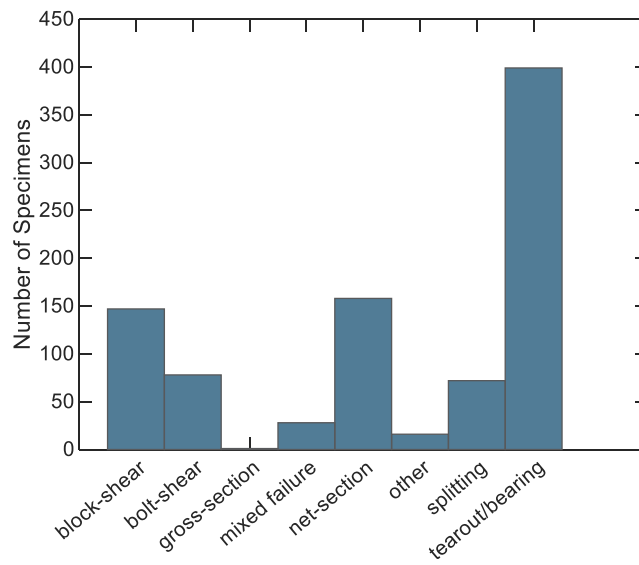


*Figure 7: Failure Modes*

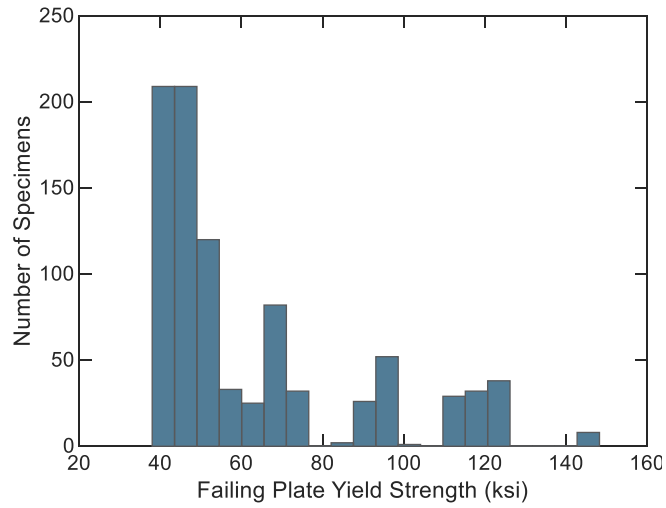


Figure 8: Plate Yield Strength

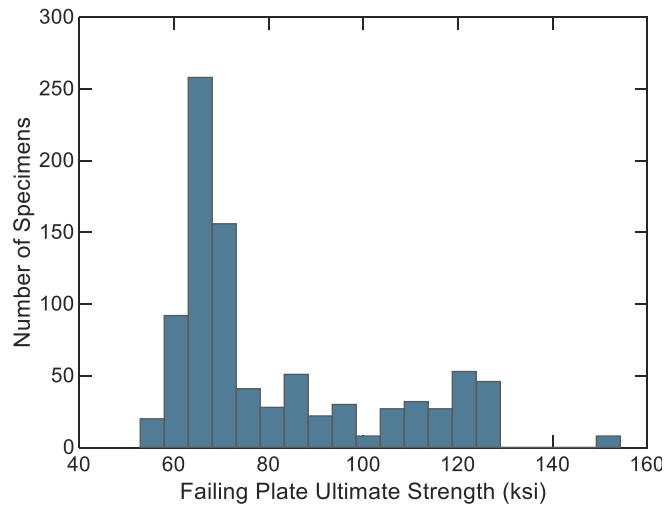


Figure 9: Plate Ultimate Strength

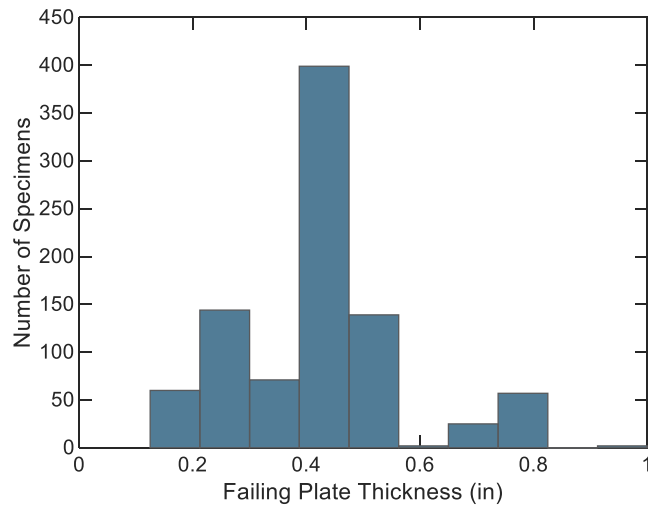


*Figure 10: Plate Thickness*

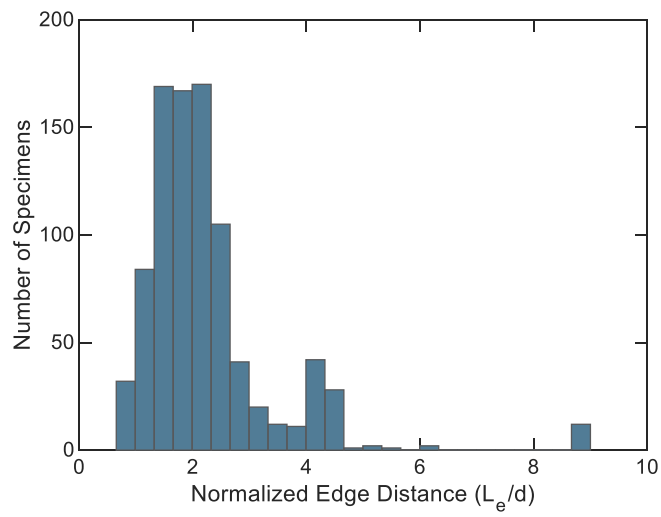


*Figure 11: Normalized Edge Distance*

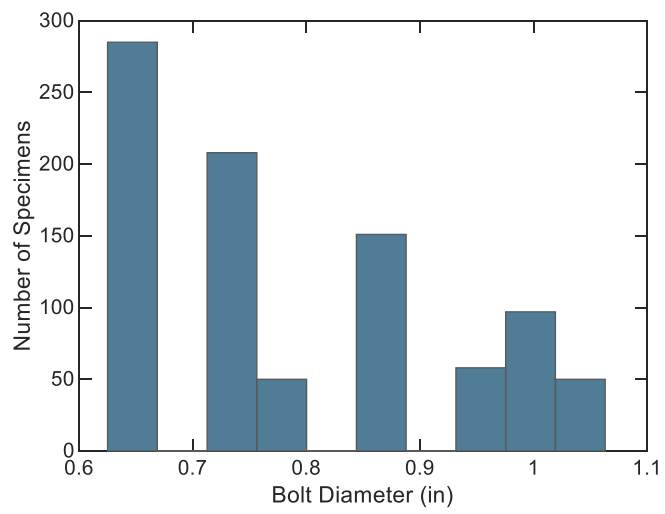


*Figure 12: Bolt Diameter*

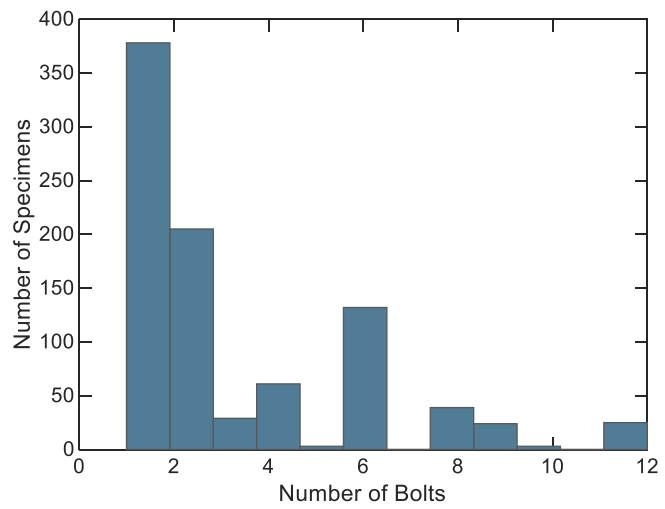


*Figure 13: Number of Bolts*

The figures demonstrate that a wide variety of conditions were tested in existing research. However, only 471 of the 899 concentrically loaded specimens failed in bearing, tearout, or the related splitting type failure. This limited the database size for analysis of these limit states.

### **Eccentrically Loaded Connections**

A literature review was also performed for eccentrically loaded connections. The purpose of the eccentrically loaded connections database was to have a qualitative representation of the existing literature for investigation and future research. Eccentrically loaded connections increase the complexity of the tearout limit state because the direction and magnitude of the bolt force will vary between bolts. The Instantaneous Center of Rotation method offers a solution but is applied only for the bolt shear limit state in the current AISC *Specification* (AISC 2016).

Several experimental testing methods exist for eccentrically loaded connections. The most direct method involves loading a bolted cantilevered plate at a certain distance from the support. The plate is directly subject to an eccentricity and rotation that must be accommodated by deformation of the bolt holes, bolts and plate. A more common procedure is to apply a load to a beam fastened to two columns with a plate or angle. A pinned column base and short beam is used such as to induce a rotation at the column base. The reaction force on the column is at a certain distance, or eccentricity, from the centroid of the bolt group. An example of this type of test is shown in Figure 14. Finally, the effects of eccentricity can also be tested in shear connections often used in structures. In which case, a longer span beam is loaded to induce a deflection of the beam and rotation at the

connection. Although these tests are larger, they can simulate a common structural element. All these test methods can be completed with various connections elements. The most commonly used are single plates bolted to the beam and welded to the supporting member, and all-bolted single or double angles.

### ***Review of Database Specimens***

Two datasets were created to organize the information. The first dataset is comprised of single plate bolted shear connections. The other dataset consists of the basic eccentrically loaded bolted groups which do not include single plate shear connections (i.e., using the first two methods described in the previous section). Specimens were required to meet the criteria for the database as described earlier. Additionally, in order to maintain comparison between reviewed specimens, the following were not included in the database:

- Single plate shear connections that included stiffeners, slabs, or tabs
- Specimens subject to other loading such as compression

Other shear connections, such as single and double angle, were reviewed as well but not compiled in a database. Due to the variation of tests for eccentrically loaded connections, the literature was reviewed for testing procedures, connection design, proposed analysis methods, and failure information that was relevant to the scope of this project.

A brief summary of the tests included in the database are provided in this section. The basic eccentrically loaded bolt groups do not rely on the beam stiffness to achieve rotation and constitute a simplified approach to studying the effects of eccentricity. Crawford & Kulak's (1971) method used in the *AISC Specification*, which is based on

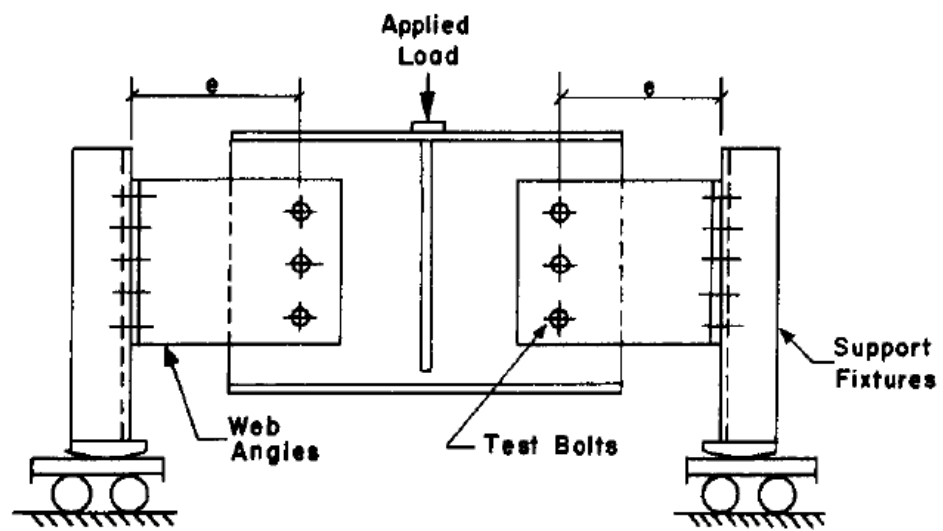


*Figure 14: Eccentrically Loaded Shear Connection Set-Up (Crawford and Kulak 1971)*

bolt shear strength. Wing and Harris (1983) and Badawi (1983) investigated bearing failures in eccentrically loaded connections. In both studies, a thinner plate was used compared to the other reviewed works. Both papers considered failure as a 0.3 in. deformation of the furthest bolt from the centroid, and the failure was noted to be bearing, indicating that can be a bearing is a limiting factor in eccentrically loaded connections. Although the edge distance value was not given, the connections were described as standard. It is likely that the edge distance sufficed to preclude tearout failure. Research by Nissen (2014) used several bolt lines and rows, resulting in block shearing and large deformations. The studies are summarized in Table 3. Studies on shear connections can provide a more practical investigation of the limit states.

A summary of experimental testing conducted on single plate shear connections is presented in Table 4. The table shows that the frequency of bearing and tearout in existing single plate shear connection research is limited. Although bearing deformations were noticed in several of the tests, only one test by Sherman and Ghorbanpoor (2002) was described as a bearing failure. Tearout was not a failure in any of the single plate shear connection tests investigated. The data suggests that tearout was precluded with use of center-to-edge distances of  $2d$  and/or stronger plate material. The specimens with smaller edge distances had a plate thickness of at least  $3/8$  in. No testing in these datasets used a plate thinner than  $3/8$  in. in combination with shorter edge distances, which would be more predisposed to a bearing or tearout failure. The only tests that tested the minimum edge distance were in Baldwin Metzger's research. However, the horizontal distance was set at  $2d$ .

Table 3: Summary of Basic Eccentrically Loaded Bolt Groups

| Author           | Year   | # of Tests | Testing Details           | Thinnest Material | Eccentric.   | Smallest Edge Dist. | Failure Modes |
|------------------|--------|------------|---------------------------|-------------------|--------------|---------------------|---------------|
| Crawford & Kulak | (1971) | 8          | Double Angles             | 0.50" A36         | 8" - 15"     | Not Given           | Bolt Shear    |
| Badawi           | (1983) | 12         | Double Angles             | 0.305" Gr.50      | 3.5" - 11.8" | Not Given           | Bearing       |
| Wing & Harris    | (1983) | 12         | Double Angles             | 0.287" Gr.50      | 2.5" - 6.5"  | Not Given           | Bearing       |
| Nissen           | (2014) | 11         | Cantilevered Single Plate | 0.394" S325       | 8" - 15.75"  | 2.66d (horiz.)      | Block Shear   |

Note:

1. Bolts in Nissen 2014 are M12 Gr. 10.9. All other tests used 3/4" diameter A325

Table 4: Summary of Single Plate Shear Connections

| Author                | Year   | # of Tests | Testing Details  | Thinnest Material | Eccentric. | Smallest Edge Dist.                          | Failure Modes                |
|-----------------------|--------|------------|------------------|-------------------|------------|----------------------------------------------|------------------------------|
| Astaneh-Asl et al.    | (1988) | 5          | Cantilever Beam  | 0.375" A36        | 2.75"      | 1.5 <i>d</i>                                 | Bolt Shear                   |
| Porter & Astaneh-Asl  | (1990) | 4          | Cantilever Beam  | 0.375" A36        | 3.125"     | 1.5 <i>d</i>                                 | Bolt Shear                   |
| Sherman & Ghorbanpoor | (2002) | 8          | Simply Supported | 0.371" A36        | 6.3" - 10" | 2 <i>d</i>                                   | Other <sup>3</sup> , Bearing |
| Creech                | (2005) | 8          | Simply Supported | 0.375" A36        | 3"         | 2 <i>d</i>                                   | Bolt Shear<br>Beam Failure   |
| Baldwin Metzger       | (2006) | 8          | Simply Supported | 0.39" Gr.50       | 3" - 10.5" | 1.33 <i>d</i> (vert.)<br>2 <i>d</i> (horiz.) | Beam Failure,<br>Bolt Shear  |
| Marosi                | (2011) | 6          | Cantilever Beam  | 0.247" Gr.50      | 2" - 4"    | 2 <i>d</i>                                   | Other <sup>3</sup>           |
| Hertz                 | (2014) | 3          | Cantilever Beam  | 0.37" Gr.50       | 6" - 8"    | 2 <i>d</i>                                   | Other <sup>3</sup>           |

## Notes:

1. Bolt holes are short-slotted in Porter & Astaneh-Asl (1990) and Sherman & Ghorbanpoor (2002)
2. Bolts in Marosi (2011) and Hertz (2014) range from 3/4" to 1" and 3/4" to 7/8" diameter A325, respectively. All other tests used 3/4" diameter A325
3. Other failures may include plate twisting, column failure, plate buckling, plate shear rupture, plate flexure, and weld fracture

Other failure modes, particularly plate failures, were more common with extended configurations in which the eccentricity to the center of the bolt group was greater than 3 in. This includes the extended configurations tested by Sherman & Ghorbanpoor (2002), Hertz (2014), and several of Marosi's (2011) specimens. Beam failures were also observed in some tests, due to insufficient lateral bracing and attempting to achieve target rotations of 0.03 radians. Single plate shear connections are planned for the second stage of this research project. Nevertheless, literature on other connection types (single and double angles) was also reviewed since the limit state of bearing and tearout has been more thoroughly researched in these connections.

### ***Review of Single and Double Angle Bolted Connections***

Birkemoe and Gilmor (1978) completed tests on a coped and uncoped double angle connection which demonstrated horizontal splitting type failures of the beam edge and large deformations. The beam was a W18x45 of grade 44W (44 ksi nominal yield stress) with a measured web thickness of 0.305 in. The edge distance from the center of bolt to edge of the beam web was 1-3/4 in. or  $2.33d$ . Comparing to the single plate shear connections in Table 4, the failing material was thinner but the edge distance was higher than most specimens. The test is most comparable to the ones completed by Badawi (1983) and Wing and Harris (1983), which failed with bearing deformation. The use of double angles may help preclude other failure modes of the plate and beam web, and isolate the failure to bearing, tearout, and bolt shear rupture.

Franchuk et al. (2002) investigated five single angle bolted connections with slotted holes and minimum edge distances for 1 in. and  $\frac{3}{4}$  in. diameter bolts. The failing angles

had a thickness of 1/4 in. with 350W steel material. Two of the tests failed in tearout of the bottom bolt combined with tilting of the middle bolt and out-of-plane movement of the angle, shown in Figure 15. The use of a thinner single angle caused the bending behavior of the angle; however, the use of minimum edge distances most likely resulted in the tearout failure.

Man et al. expanded on Franchuk's work of angle connections with slotted holes by testing numerous other conditions, including edge distance, use of plate washers, slot length, pretension, among others. Several specimens used the minimum edge distance of 32 mm (1.25 in.) for a 7/8 in. diameter bolt. Unlike Franchuk et al., Man et al. tested mostly 9.5 mm angle thicknesses (3/8 in.) of 300W steel grade. This is more pertinent to design since the AISC *Specification* (AISC 2016) suggests a minimum of 3/8 in. angle. The bolt tilting and angle bending observed in Franchuk et al. was not precluded with the use of the thicker angle. Nevertheless, tearout of the bottom edge was seen in the tests. The remaining tests by Man et al. demonstrated the potential of horizontal tearout of the beam web using edge distances slightly larger than the minimum, as was seen by Birkemoe and Gilmor.

### ***Summary***

Tearout and bearing has been studied in single and double angle connection. For the double and single angles, the current *Specification* (AISC 2016) does not set any provisions to account for the varying tearout lengths in eccentrically loaded connections. Man et al. proposed accurate methods but are based on the studies completed with slotted holes. Tearout in single plate shear connections has not been found in the literature review. The current AISC *Specification* treats tearout and bearing as concentric for single plate



(a) Test IV – Angle



(b) Test V – Angle

*Figure 15: Tests by Franchuk et al. showing tearout of the bottom bolt and bolt tilting*

shear connections. Further testing of single plate shear connections subject to tearout failures can provide insight to the behavior and to the accuracy of different design methods.

### **Alternative Tearout Lengths**

Under the current AISC Specification (AISC 2016), strength for the limit state of tearout is based on the clear distance, in the direction of force, between the edge of the bolt hole and the edge of the adjacent hole or edge of the material. This distance is denoted as  $l_c$ . For the case illustrated in Figure 16, the clear distance is computed as a function of the edge distance,  $L_e$ , and the diameter of the hole,  $d_h$ :

$$l_c = L_e - \frac{d_h}{2} \quad (11)$$

Examination of experimental results has shown that the length of failure planes from specimens that exhibited tearout are somewhat longer than the clear distance. Researchers have proposed various alternative lengths, that when used in lieu of  $l_c$ , provide a more accurate assessment of strength. The first alternative tearout length that is investigated in this work, denoted as  $l_{v1}$ , was proposed by Kamtekar (2012) and is equal to the clear distance, in the direction of force, between the edge of the bolt hole and the edge of the adjacent hole or edge of the material along lines tangent to the bolt. For the case illustrated in Figure 16,  $l_{v1}$  is computed as:

$$l_{v1} = L_e - \frac{\sqrt{d_h^2 - d^2}}{2} \quad (12)$$

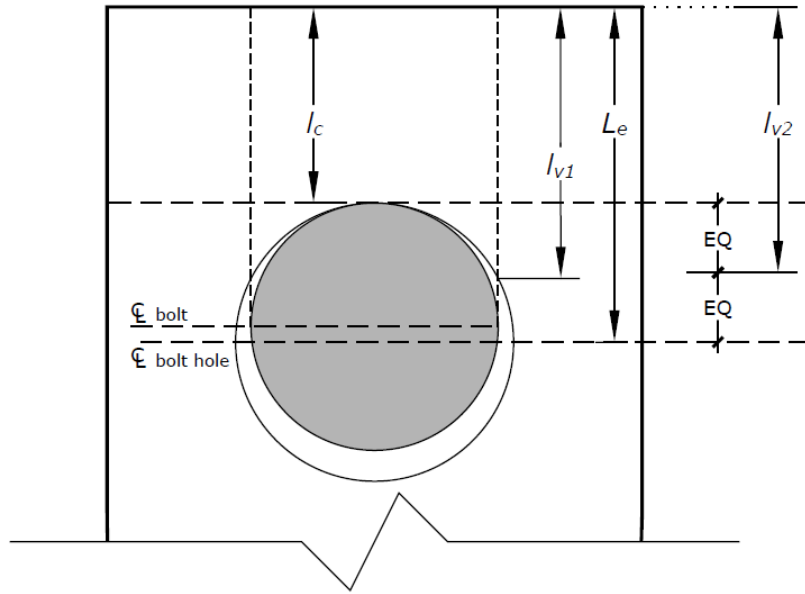


Figure 16: Tearout Length Comparison

The second alternative tearout length, denoted as  $l_{v2}$ , was proposed by Clements and Teh (2013) and is equal to the average of the clear distance,  $l_c$ , and the edge distance,  $L_e$ . For the case illustrated in Figure 16, this is computed as:

$$l_{v2} = L_e - \frac{d_h}{4} \quad (13)$$

Elliot et al. (2019) evaluated the use of  $l_{v1}$  and  $l_{v2}$  in strength equations for a small set of experiments that failed in tearout. They found them both to provide similarly improved predictions of tearout strength in comparison to current equations. They also evaluated alternative net areas for block shear rupture that are similar in concept to the alternative tearout lengths.

Other tearout lengths have been proposed (e.g., Duerr 2006). However, differences among the lengths are slight. Also, some are more complicated than  $l_{v1}$  and  $l_{v2}$  to compute for general bolted connections. Therefore, this work focuses on evaluating  $l_c$ ,  $l_{v1}$ , and  $l_{v2}$ .

## CHAPTER III: EVALUATION OF PUBLISHED EXPERIMENTS

### Overview

Hundreds of physical experimental tests on concentrically loaded bolted connections susceptible to tearout have been performed in past research. This data has been collected and organized into a database for the purpose of evaluating alternative tearout lengths. Only connections categorized as failing in bearing, tearout, or splitting were utilized in this analysis. The limit state of splitting is distinct from the limit state of tearout. Equations have been proposed to predict splitting strength (Duerr 2006) and some standards treat tearout and splitting separately (e.g., ASME 2017). However, splitting is not recognized within the *AISC Specification* (AISC 2016). Therefore, equations for the limit state of tearout are implicitly covering splitting as well. This approach is justified since experimental results have shown the two limit states to have similar strengths and splitting failures are typically included in the evaluation of the tearout equations, as is done in this work. Of the 899 specimens in the concentrically loaded database, 471 failed in bearing, tearout, or splitting, as documented in Table 2. The remaining specimens experienced other failure modes including bolt shear rupture, tensile yielding, tensile rupture, and curling.

### Strength of Single-Bolt Specimens

Specimens with a single bolt in the direction of force allow for a direct evaluation of individual limit states. These specimens are evaluated separately from specimens with multiple bolts in the direction of force which may experience multiple limit states (e.g., bearing and tearout). Of the 471 specimens in the database with bearing, tearout, or splitting failures, 313 contained a single bolt in the direction of force. Of these single-bolt

specimens,  $R_{exp,d}$  was available for 223,  $R_{exp,u}$  was available for 301, and both loads were available for 211 of the specimens. The analysis included 265 specimens with one bolt perpendicular to the line of force and 48 with two bolts perpendicular to the line of force. These specimens include many that do not meet current requirements in the AISC *Specification* (AISC 2016) for minimum edge distance and bolt installation (i.e., installed to a snug-tight condition or pretensioned).

Experimentally obtained strengths are compared to strengths computed from various instances of a generic bearing and tearout strength equation given by Eq. (14).

$$R_n = C_t l_x t F_u \leq C_b d t F_u \quad (14)$$

where,  $C_t$  is the coefficient applied to the tearout strength,  $l_x$  is the length used for determining tearout strength (i.e., either  $l_c$ ,  $l_{v1}$ , or  $l_{v2}$ ), and  $C_b$  is the coefficient applied to the bearing strength.

The test-to-predicted ratio (TTP) for each specimen is computed as the ratio of the experimentally obtained strength to the strength from Eq. (14) for various selections of  $C_t$ ,  $l_x$ , and,  $C_b$ . The mean and coefficient of variation (COV) of the test-to-predicted ratio across the specimens is presented in Table 5 for comparisons to the load at 1/4 in. deformation and Table 6 for comparisons to the ultimate load.

Two values of the mean and COV are presented. The value outside the parentheses includes data from specimens that did not meet AISC *Specification* (AISC 2016) requirements for minimum edge distance. The value inside the parentheses excludes specimens that did not meet the requirements.

Table 5: Test-to-Predicted Ratio Statistics for Various Evaluations of the Load at 1/4 in. Deformation for Single-Bolt Specimens (data from 223 specimens, data from 192 specimens meeting minimum edge distance requirements in parentheses)

|                        | $X_t$ | $l_x$    | $X_b$ | Mean TTP      | COV TTP       |
|------------------------|-------|----------|-------|---------------|---------------|
| Current Equations      | 1.2   | $l_c$    | 2.4   | 1.223 (1.180) | 0.186 (0.172) |
| Current Coefficients   | 1.2   | $l_{v1}$ | 2.4   | 0.952 (0.953) | 0.137 (0.144) |
| Current Coefficients   | 1.2   | $l_{v2}$ | 2.4   | 0.992 (0.988) | 0.140 (0.147) |
| Optimized Coefficients | 1.63  | $l_c$    | 2.29  | 0.957 (0.934) | 0.153 (0.144) |
| Optimized Coefficients | 1.17  | $l_{v1}$ | 2.36  | 0.975 (0.976) | 0.137 (0.144) |
| Optimized Coefficients | 1.23  | $l_{v2}$ | 2.36  | 0.975 (0.972) | 0.137 (0.144) |

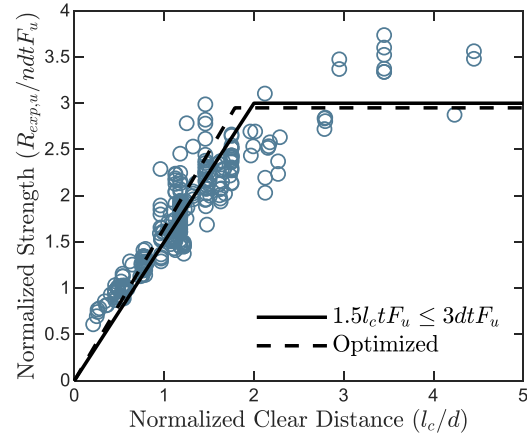
Table 6: Test-to-Predicted Ratio Statistics for Various Evaluations of Ultimate Load for Single-Bolt Specimens (data from 301 specimens, data from 234 specimens meeting minimum edge distance requirements in parentheses)

|                        | $X_t$ | $l_x$    | $X_b$ | Mean TTP      | COV TTP       |
|------------------------|-------|----------|-------|---------------|---------------|
| Current Equation       | 1.5   | $l_c$    | 3     | 1.065 (1.003) | 0.192 (0.140) |
| Current Coefficients   | 1.5   | $l_{v1}$ | 3     | 0.804 (0.812) | 0.139 (0.151) |
| Current Coefficients   | 1.5   | $l_{v2}$ | 3     | 0.841 (0.842) | 0.133 (0.144) |
| Optimized Coefficients | 1.65  | $l_c$    | 2.95  | 0.978 (0.921) | 0.189 (0.145) |
| Optimized Coefficients | 1.16  | $l_{v1}$ | 3.21  | 1.009 (1.010) | 0.117 (0.128) |
| Optimized Coefficients | 1.22  | $l_{v2}$ | 3.23  | 1.010 (1.005) | 0.120 (0.129) |
| Rounded Coefficients   | 1.2   | $l_{v1}$ | 3     | 0.981 (0.984) | 0.119 (0.130) |
| Rounded Coefficients   | 1.2   | $l_{v2}$ | 3     | 1.030 (1.025) | 0.120 (0.129) |

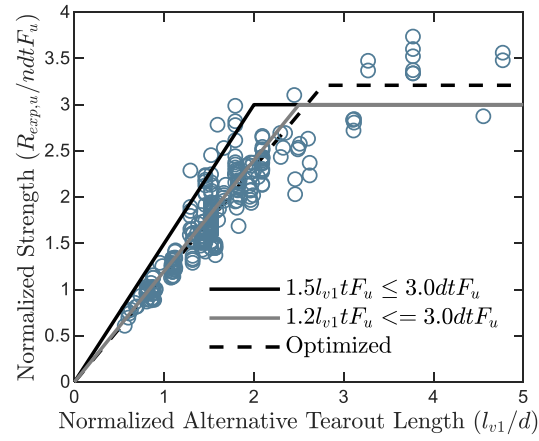
The data is also presented in Figure 17 and Figure 18, where the experimentally obtained strength is normalized against the value of  $dtF_u$  and plotted against normalized edge distance. Where the specimen included multiple bolts perpendicular to the direction of load, the experimental strengths were divided by the number of bolts in the connection,  $n$ , for plotting purposes.

Optimized coefficients are among the instances of Eq. 14 that are compared in Table 5, Table 6, Figure 17, and Figure 18 . Six sets of optimized coefficients were computed, one for each of the three tearout lengths (i.e.,  $l_c$ ,  $l_{v1}$ , and  $l_{v2}$ ) at the ultimate and 1/4 in. deformation levels. The coefficients were obtained using a numerical optimization to minimize the sum over all specimens of the square of the difference between the test-to-predicted ratio and unity. Single-bolt and multiple-bolts specimens were included in the optimization.

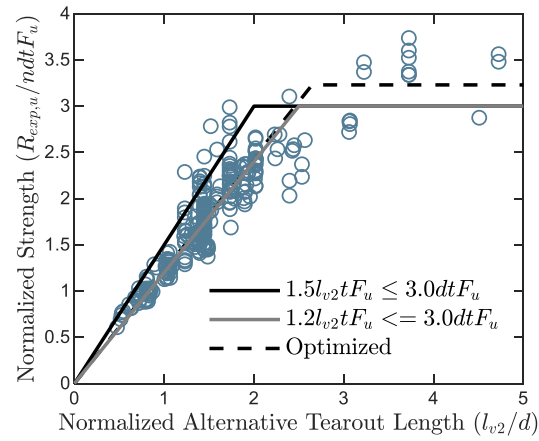
The mean test-to-predicted ratio for the current equations is 1.223 for single-bolt specimens and 1.180 for single-bolt specimens meeting minimum edge distance requirements (Table 5), indicating that current provisions for bearing and tearout are conservative in predicting the load at 1/4 in. deformation. This is also seen in Figure 18 (b) where most experimental data are above the line representative of current design equations. This is especially true for specimens with smaller edge distances. Either of the two alternative tearout lengths (i.e.,  $l_{v1}$  or  $l_{v2}$ ) provides a more accurate and precise assessment of strength when using the current coefficients as seen in both a mean value of the test-to-predicted ratio that is closer to unity and a COV of the test-to-predicted ratio that is lower than for the current equations. However, the use of  $l_{v1}$  with current coefficients somewhat



(a) Ultimate Load,  $l_c$

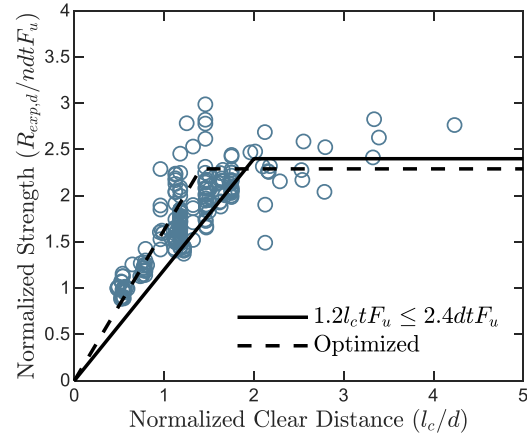


(b) Ultimate Load,  $l_{v1}$

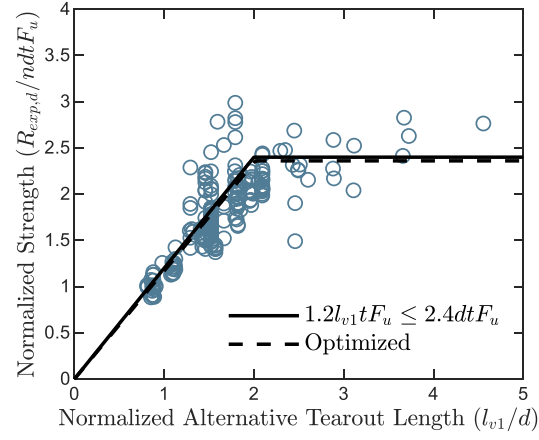


(c) Ultimate Load,  $l_{v2}$

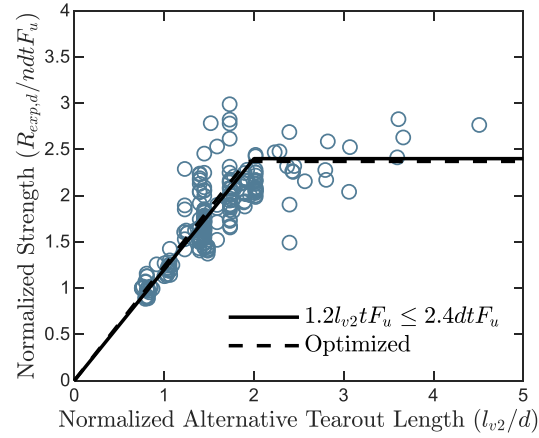
Figure 17: Normalized Strength Comparisons Between Tearout Lengths for Ultimate Load



(a) Load at 1/4 in. Deformation,  $l_c$



(b) Load at 1/4 in. Deformation,  $l_{v1}$



(c) Load at 1/4 in. Deformation,  $l_{v2}$

Figure 18: Normalized Strength Comparisons Between Tearout Lengths for Ultimate Load

overestimates the strength. Results with the optimized coefficients indicate that current coefficients are generally appropriate for use with  $l_{v1}$  or  $l_{v2}$ .

Similar trends are seen when comparing to the ultimate load (Table 6). A key difference is that the current coefficients with the alternative tearout lengths result in a significant overestimation of strength. Rather, a coefficient of 1.2, the same as is used in the equations for load at the 1/4 in. deformation limit state, can provide an accurate prediction of strength with less variation than the current equation.

These results suggest that the difference between the load at 1/4 in. deformation and the ultimate load is far smaller than implied by current provisions. Figure 19 shows the ratio  $R_{exp,u}/R_{exp,d}$  for single-bolt specimens plotted against the normalized clear distance. The ratio of ultimate load to load at 1/4 in. deformation is 1.25 according to the current *AISC Specification* (AISC 2016) (i.e., the ratio between Eq. (9) and Eq. (10) equals 1.25). However, the experimental ratios are lower, especially for cases with smaller edge distances. However, the experimental ratios are lower, especially for cases with smaller edge distances. Only 6 of the 211 specimens plotted have a ratio greater than 1.25.

### **Strength of Multiple-Bolt Specimens**

Of the 471 specimens in the database with bearing, tearout, or splitting failures, 158 have more than one bolt in the direction of force. Of these multiple-bolt specimens,  $R_{exp,d}$  was available for 100,  $R_{exp,u}$  was available for 136, and both loads were available for 78 of the specimens.

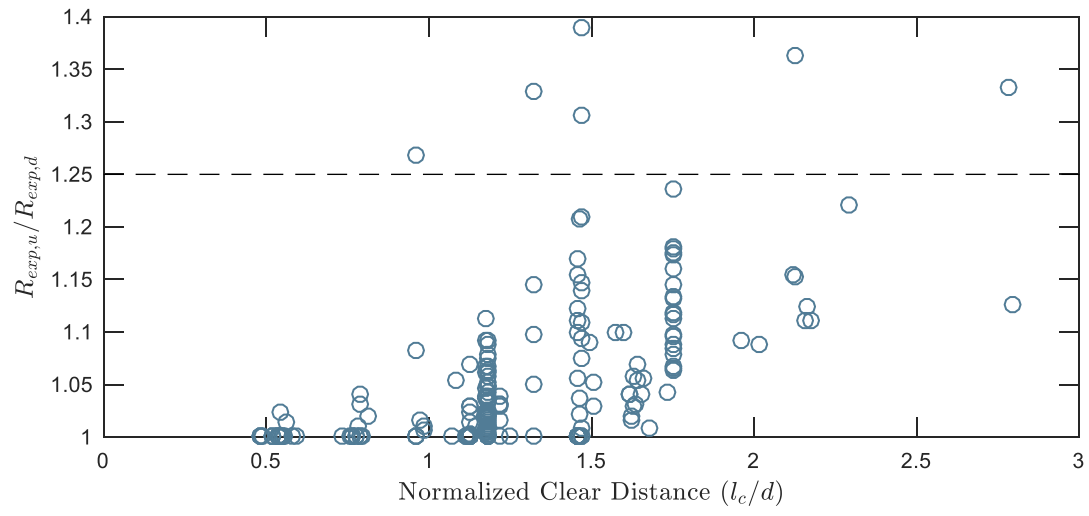


*Figure 19: Ratio of Ultimate Load and 1/4 in. Deformation versus Normalized Clear Distance*

Table 7 and Table 8 provide summary statistics for the test-to-predicted ratios computed using the various instances of Equation 14 for multiple-bolt specimens. The values of the COV are approximately the same as those for the single-bolt cases, indicating a good fit of the data. At the ultimate load, when including all specimens, and with rounded coefficients, the mean test-to-predicted ratio is 0.927 for  $l_{v1}$  and 0.954 for  $l_{v2}$ . These values are lower than that for the single-bolt case and lower than is generally acceptable. A possible reason for this is deformation compatibility between bolts. Achieving the full bearing strength of  $3.0dtF_u$  requires significant deformation. It is possible, for example, that by the time the full bearing capacity of the interior bolts is achieved, the end bolts have passed their peak strength and contribute only a lower post-peak strength. Nonetheless, when specimens not meeting minimum edge distance and spacing requirements are excluded, the mean test-to-predicted ratios are slightly above unity.

Previous editions of the *AISC Specification* included exceptions to tearout provisions when enough bolts were in a line and certain geometric conditions were met. It was theorized that if the interior bolts fail in bearing, the tearout strength of the end bolt would be less critical. To investigate the effect of neglecting tearout, a test-to-predicted ratio equal to the load at 1/4 in. deformation divided by the bearing strength (the result of Eq. (7) times the number of bolts in the connection) is plotted against the normalized clear distance in Figure 20. Only specimens meeting the minimum edge distance and minimum spacing requirements of the current *AISC Specification* (AISC 2016) are plotted. Specimens that meet the criteria for the tearout exception in the 1993 edition of the *Specification* (AISC 1993) (i.e., two or more bolts in a line, edge distance greater than  $1.5d$ ,

Table 7: Test-to-Predicted Ratio Statistics for Various Evaluations of the Load at 1/4 in. Deformation for Multiple-Bolt Specimens (data from 100 specimens, data from 62 specimens meeting minimum edge distance and spacing requirements in parentheses)

|                        | $X_t$ | $l_x$    | $X_b$ | Mean TTP      | COV TTP       |
|------------------------|-------|----------|-------|---------------|---------------|
| Current Equations      | 1.2   | $l_c$    | 2.4   | 1.137 (1.106) | 0.155 (0.159) |
| Current Coefficients   | 1.2   | $l_{v1}$ | 2.4   | 0.973 (1.013) | 0.127 (0.126) |
| Current Coefficients   | 1.2   | $l_{v2}$ | 2.4   | 0.992 (1.024) | 0.122 (0.127) |
| Optimized Coefficients | 1.63  | $l_c$    | 2.29  | 1.032 (1.048) | 0.122 (0.129) |
| Optimized Coefficients | 1.17  | $l_{v1}$ | 2.36  | 0.992 (1.033) | 0.126 (0.126) |
| Optimized Coefficients | 1.23  | $l_{v2}$ | 2.37  | 0.995 (1.032) | 0.125 (0.127) |

Table 8: Test-to-Predicted Ratio Statistics for Various Evaluations of Ultimate Load for Multiple-Bolt Specimens (data from 136 specimens, data from 48 specimens meeting minimum edge distance and spacing requirements in parentheses)

|                        | $X_t$ | $l_x$    | $X_b$ | Mean TTP      | COV TTP       |
|------------------------|-------|----------|-------|---------------|---------------|
| Current Equations      | 1.5   | $l_c$    | 3     | 1.011 (1.047) | 0.140 (0.172) |
| Current Coefficients   | 1.5   | $l_{v1}$ | 3     | 0.812 (0.951) | 0.188 (0.178) |
| Current Coefficients   | 1.5   | $l_{v2}$ | 3     | 0.829 (0.961) | 0.182 (0.178) |
| Optimized Coefficients | 1.65  | $l_c$    | 2.95  | 0.958 (1.029) | 0.148 (0.179) |
| Optimized Coefficients | 1.16  | $l_{v1}$ | 3.21  | 0.937 (1.003) | 0.138 (0.164) |
| Optimized Coefficients | 1.22  | $l_{v2}$ | 3.23  | 0.928 (1.000) | 0.140 (0.166) |
| Rounded Coefficients   | 1.2   | $l_{v1}$ | 3     | 0.927 (1.015) | 0.145 (0.168) |
| Rounded Coefficients   | 1.2   | $l_{v2}$ | 3     | 0.954 (1.038) | 0.144 (0.168) |

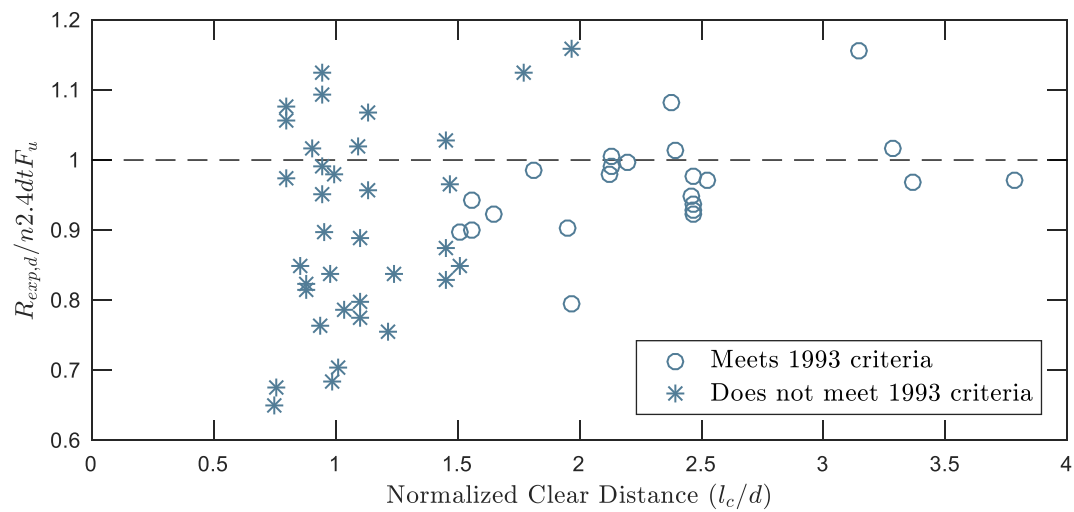


Figure 20: Test-to-Predicted Ratio Excluding Tearout versus Normalized Clear Distance

and spacing greater than  $3d$ ) are differentiated with circular markers. The figure shows significant variation; however, many of the specimens have low test-to-predicted ratios, including several that meet the criteria in the 1993 *Specification*.

To summarize, increased accuracy in predicting tearout strength was achieved using either  $l_{v1}$  or  $l_{v2}$  with a coefficient on the tearout strength of 1.2. This was shown to be true for both the ultimate load and the load at 1/4 in. deformation. Based on these initial results, the remaining analyses are conducted with the following equations for tearout strength:

$$R_n = 1.2l_{v1}tF_u \quad (15)$$

$$R_n = 1.2l_{v2}tF_u \quad (16)$$

### **Effects of Bolt Tightening**

The AISC *Specification* (AISC 2016) requires that bolts be installed to a snug-tight condition or pretensioned. Many of the experiments in the database utilize untightened bolts or had a gap between the plates. These loose connections do not satisfy the requirements of the AISC *Specification*, but help minimize the contribution of friction to the strength of the connection and better evaluate the strength of the connected material alone.

Frank and Yura (1981) tested connections with different levels of tightening, although loose connections were not considered. They found that specimens with pretensioned bolts had 10% higher capacity at 1/4 in. deformation when compared to snug-tightened bolts but that the ultimate capacity was unaffected by the level of tightening.

Table 9 presents a comparison of experimental strength to strength equations from the current *AISC Specification* (AISC 2016) for all 471 specimens in the database that failed in bearing, tearout, or splitting. No clearly identifiable trend is seen in the mean test-to-predicted ratios at ultimate load. However, as observed by Frank and Yura (1981), the mean test-to-predicted ratios for the load at 1/4 in. deformation tend to increase as the level of tightening increases.

### **Mixed Failures**

Several multiple-bolt specimens tested by Cai and Driver (2008) exhibited mixed failures of bearing or tearout of the end bolts and shear rupture of the interior bolts. This mode of failure is a validation of the premise underlying the use of effective strengths of individual bolts when computing the strength of a bolt group. These specimens were not included in the preceding discussion because they exhibited mixed failures. However, they are examined here to validate the use of the alternative tearout lengths for connections where a mixed failure may occur. The connected material in which the failures occurred was the web of a wide flange with a measured thickness of 0.36 in. and a measured ultimate tensile strength of 74.11 ksi. The connections each had six 3/4 in. diameter bolts (two lines of three) in standard holes. The shear strength of the bolts was measured to be 50.13 kips. Most of these specimens reached their ultimate capacity prior to reaching 1/4 in. deformation, so only ultimate load was considered.

Table 9: Mean values of test-to-predicted ratios based on level of tightening

| Load Level          | Pretensioned | Snug-Tightened | Untightened/Loose |
|---------------------|--------------|----------------|-------------------|
| Ultimate            | 1.049        | 1.023          | 1.067             |
| 1/4 in. Deformation | 1.246        | 1.197          | 1.157             |

Table 10 summarizes the specimens along with test-to-predicted ratios calculated using different computed strengths. The test-to-predicted ratios presented in Table 10 were calculated with tearout strength given by the current equation (i.e., Eq. (10)) as well as equations with the alternative tearout lengths (i.e., Eqs. (15) and (16)). Also included in Table 10 are test-to-predicted ratios computed with the predicted strength taken as the lower of the strengths for the bolt group for 1) the limit states of bearing and tearout and 2) the limit state of bolt shear rupture.

The results of these specimens show that it is indeed unconservative to treat bearing and tearout separate from bolt shear rupture, given that doing so results in a 10% overprediction of strength on average. Using this method, specimens C1E1a, C2E1b, and C3E1c were controlled by bearing and tearout strength and the rest were controlled by bolt shear rupture strength. More accurate but still somewhat unconservative results are obtained when considering the potential of mixed failures and summing the effective strengths of each individual bolt to obtain the strength of the bolt group. Little difference is seen between the use of the clear distance and either of the two alternative tearout lengths, all three result in a 4 to 5% overprediction of strength on average.

Table 10: Analysis of specimens tested by Cai and Driver (2008) that exhibited mixed failures

| Specimen | $L_e$ (kips) | $R_{exp,u}$ (kips) | Using $l_c$<br>Eq. (10) <sup>a</sup> | Test-to-predicted ratio |                            |                            |
|----------|--------------|--------------------|--------------------------------------|-------------------------|----------------------------|----------------------------|
|          |              |                    |                                      | Using $l_c$<br>Eq. (10) | Using $l_{v1}$<br>Eq. (15) | Using $l_{v2}$<br>Eq. (16) |
| C1E1a    | 1.00         | 243.27             | 0.850                                | 0.981                   | 0.955                      | 0.968                      |
| C2E1b    | 1.00         | 249.94             | 0.866                                | 1.005                   | 0.978                      | 0.992                      |
| C3E1c    | 1.00         | 250.17             | 0.868                                | 1.007                   | 0.981                      | 0.993                      |
| C4E2a    | 1.25         | 279.80             | 0.930                                | 1.044                   | 1.035                      | 1.047                      |
| C5E2b    | 1.26         | 267.61             | 0.890                                | 0.993                   | 0.984                      | 0.996                      |
| C6E2c    | 1.26         | 259.05             | 0.861                                | 0.965                   | 0.955                      | 0.968                      |
| C7E3a    | 1.50         | 272.40             | 0.906                                | 0.946                   | 0.950                      | 0.962                      |
| C8E3b    | 1.50         | 259.74             | 0.864                                | 0.903                   | 0.908                      | 0.917                      |
| C9E3c    | 1.51         | 273.21             | 0.908                                | 0.947                   | 0.952                      | 0.962                      |
| C10E4a   | 1.76         | 273.14             | 0.908                                | 0.908                   | 0.908                      | 0.912                      |
| C11E4b   | 1.75         | 280.81             | 0.934                                | 0.934                   | 0.934                      | 0.937                      |
| C12E4c   | 1.75         | 265.90             | 0.884                                | 0.884                   | 0.884                      | 0.887                      |
| C13E5a   | 2.00         | 290.70             | 0.966                                | 0.966                   | 0.966                      | 0.966                      |
| C14E5b   | 2.00         | 267.03             | 0.888                                | 0.888                   | 0.888                      | 0.888                      |
| C15E5c   | 2.01         | 287.71             | 0.957                                | 0.957                   | 0.957                      | 0.957                      |
| C16E6    | 2.76         | 297.49             | 0.989                                | 0.989                   | 0.989                      | 0.989                      |
| Mean:    |              |                    | 0.904                                | 0.957                   | 0.952                      | 0.959                      |

<sup>a</sup> The predicted strengths for these test-to-predicted ratios were computed without considering potential interaction between the limit states of bearing and tearout and the limit state of shear rupture of the bolt.

## CHAPTER IV: EXPERIMENTAL TESTS

### Overview

The evaluation of published experiments showed that tearout equations using  $l_{v1}$  and  $l_{v2}$  had similarly improved results in comparison to the current equations. The database contains results from hundreds of experiments across a broad range of parameters. However, it only contains specimens with standard holes because the vast majority of concentrically loaded steel bolted connection tests failing in bearing, tearout, or splitting were performed with standard holes.

For connections with standard holes,  $l_{v1}$  is greater than  $l_{v2}$ . The difference between the two varies only slightly based on the diameter of the bolt; differing by a maximum of 7% for connections that satisfy minimum edge distance requirements and bolts as large as 1.5 in. diameter. The variation is greater, although still relatively small, over a range of hole types. To address this gap in data, a series of experimental tests was conducted to evaluate tearout strength for connections with different hole types.

### Test Matrix

Tension tests of 22 single-bolt butt splice connections with different hole types and edge distances were completed. The specimens consisted of two outer pull plates and a single interior test plate as shown in Figure 21. Specimens included those with standard holes and holes with minimal clearance, where the value of  $l_{v1}$  is greater than  $l_{v2}$ . Also included were specimens with oversize holes, holes with 1/8 in. more clearance than oversize holes, and short-slotted holes oriented perpendicular to the load, where the value of  $l_{v2}$  is greater than  $l_{v1}$ .

The test matrix is presented in Table 11. Two main variables are considered: the type of bolt hole and the edge distance. Four edge distances were investigated for each of the five bolt hole types. Nominal values of the edge distances were: 1 in., 1.25 in., 1.5 in., and 2 in. The smallest edge distance (1 in.) is equal to the minimum edge distance permitted by the AISC *Specification* (AISC 2016) for a 3/4 in. bolt in a standard hole. Note that the 1 in. edge distance is not permitted for oversize holes but was used in these tests for consistency. For a 3/4 in. bolt in a standard hole, the transition between tearout and bearing occurs at an edge distance of 1.91 in. per current equations. The largest edge distance (2.0 in.) was selected to be somewhat greater than this length and thus provide a comparison to a bearing-controlled failure. Two additional tests beyond the main set of 20 were also completed. Specimen NC2b was a duplicate of NC2a to investigate repeatability. Specimen STD1g was a duplicate of STD1, but with the test bolt untightened (instead of in a snug-tight condition) and greased plates to investigate the effect of reduced friction.

### **Materials and Test Setup**

The test plates were 1/4 in. thick ASTM A572 Gr. 50 steel and had a yield strength of 54.5 ksi and an ultimate tensile strength of 73.7 ksi, based on the mean of three tensile coupon tests conducted in accordance with ASTM E8 (2016). No special preparation was made to the plate surfaces before testing with the exception of specimen STD1g, where grease was applied to the faying surfaces. The test plates were installed in a universal testing machine and subjected to concentric tension load.

Table 11: Experimental Testing Summary

|                    |                | Measured Properties |           |           |           |                 |             | At 1/4" Deformation |                            |                                |                                | At Ultimate |                            |                                |                                |
|--------------------|----------------|---------------------|-----------|-----------|-----------|-----------------|-------------|---------------------|----------------------------|--------------------------------|--------------------------------|-------------|----------------------------|--------------------------------|--------------------------------|
| Name               | Hole Type      | $L_e$               | $l_c$     | $l_{v1}$  | $l_{v2}$  | $l_{v1}/l_{v2}$ | $d_h$       | $R_{exp,d}$         | TTP using $l_c$<br>(Eq. 9) | TTP using $l_{v1}$<br>(Eq. 15) | TTP using $l_{v2}$<br>(Eq. 16) | $R_{exp,u}$ | TTP using $l_c$<br>(Eq. 9) | TTP using $l_{v1}$<br>(Eq. 15) | TTP using $l_{v2}$<br>(Eq. 16) |
| ---                | ---            | <i>in</i>           | <i>in</i> | <i>in</i> | <i>in</i> | ---             | <i>in</i>   | <i>kips</i>         | ---                        | ---                            | ---                            | <i>kips</i> | ---                        | ---                            | ---                            |
| STD1               | Standard       | 1.02                | 0.615     | 0.861     | 0.818     | 1.052           | 0.812       | 19.9*               | 1.451                      | 1.036                          | 1.091                          | 19.9        | 1.160                      | 1.036                          | 1.091                          |
| STD1g <sup>1</sup> | Standard       | 0.99                | 0.578     | 0.818     | 0.784     | 1.044           | 0.823       | 17.6                | 1.359                      | 0.960                          | 1.002                          | 17.8        | 1.098                      | 0.970                          | 1.012                          |
| STD2               | Standard       | 1.16                | 0.750     | 0.992     | 0.954     | 1.039           | 0.817       | 22.9*               | 1.378                      | 1.042                          | 1.083                          | 22.9        | 1.103                      | 1.042                          | 1.083                          |
| STD3               | Standard       | 1.56                | 1.157     | 1.403     | 1.361     | 1.031           | 0.815       | 31.4*               | 1.217                      | 1.003                          | 1.034                          | 31.4        | 0.973                      | 1.003                          | 1.034                          |
| STD4               | Standard       | 2.01                | 1.605     | 1.846     | 1.810     | 1.020           | 0.818       | 37.9                | 1.128                      | 0.912                          | 0.930                          | 43.8        | 1.042                      | 1.053                          | 1.074                          |
| NC1                | No Clearance   | 1.03                | 0.650     | 0.983     | 0.838     | 1.173           | 0.753       | 20.7*               | 1.412                      | 0.933                          | 1.095                          | 20.7        | 1.129                      | 0.933                          | 1.095                          |
| NC2a               | No Clearance   | 1.32                | 0.945     | 1.278     | 1.133     | 1.128           | 0.752       | 28.9                | 1.366                      | 1.010                          | 1.139                          | 29.0        | 1.097                      | 1.014                          | 1.144                          |
| NC2b <sup>2</sup>  | No Clearance   | 1.27                | 0.901     | 1.240     | 1.087     | 1.140           | 0.744       | 26.4                | 1.291                      | 0.939                          | 1.070                          | 27.4        | 1.070                      | 0.972                          | 1.108                          |
| NC3                | No Clearance   | 1.56                | 1.185     | 1.527     | 1.373     | 1.112           | 0.752       | 33.2                | 1.248                      | 0.969                          | 1.078                          | 34.0        | 1.021                      | 0.990                          | 1.101                          |
| NC4                | No Clearance   | 2.03                | 1.661     | 2.015     | 1.848     | 1.091           | 0.747       | 41.0                | 1.218                      | 0.974                          | 0.983                          | 42.4        | 1.009                      | 1.009                          | 1.019                          |
| OVS1               | Oversize       | 1.05                | 0.584     | 0.769     | 0.819     | 0.940           | 0.938       | 20.0                | 1.537                      | 1.167                          | 1.097                          | 20.3        | 1.246                      | 1.182                          | 1.111                          |
| OVS2               | Oversize       | 1.28                | 0.813     | 1.000     | 1.045     | 0.957           | 0.928       | 24.0                | 1.298                      | 1.055                          | 1.010                          | 24.4        | 1.053                      | 1.070                          | 1.024                          |
| OVS3               | Oversize       | 1.54                | 1.079     | 1.266     | 1.311     | 0.965           | 0.929       | 29.8                | 1.223                      | 1.042                          | 1.006                          | 31.0        | 1.018                      | 1.084                          | 1.047                          |
| OVS4               | Oversize       | 2.05                | 1.590     | 1.781     | 1.821     | 0.978           | 0.923       | 36.7                | 1.088                      | 0.914                          | 0.894                          | 42.0        | 0.995                      | 1.045                          | 1.022                          |
| XOVS1              | Extra Oversize | 0.96                | 0.427     | 0.580     | 0.693     | 0.838           | 1.062       | 14.1*               | 1.487                      | 1.094                          | 0.917                          | 14.1        | 1.189                      | 1.094                          | 0.917                          |
| XOVS2              | Extra Oversize | 1.29                | 0.766     | 0.920     | 1.030     | 0.893           | 1.056       | 23.3                | 1.360                      | 1.132                          | 1.012                          | 24.2        | 1.131                      | 1.177                          | 1.051                          |
| XOVS3              | Extra Oversize | 1.51                | 0.983     | 1.138     | 1.247     | 0.913           | 1.054       | 26.2                | 1.198                      | 1.035                          | 0.945                          | 27.1        | 0.992                      | 1.071                          | 0.977                          |
| XOVS4              | Extra Oversize | 2.04                | 1.506     | 1.661     | 1.771     | 0.938           | 1.058       | 34.7                | 1.042                      | 0.938                          | 0.880                          | 36.8        | 0.885                      | 0.996                          | 0.935                          |
| SSLT1              | Short Slot     | 1.02                | 0.616     | 0.730     | 0.819     | 0.891           | 0.812×0.994 | 18.1*               | 1.316                      | 1.110                          | 0.990                          | 18.1        | 1.053                      | 1.110                          | 0.990                          |
| SSLT2              | Short Slot     | 1.31                | 0.900     | 1.015     | 1.104     | 0.919           | 0.816×0.997 | 21.4                | 1.096                      | 0.974                          | 0.893                          | 21.8        | 0.894                      | 0.992                          | 0.911                          |
| SSLT3              | Short Slot     | 1.56                | 1.151     | 1.267     | 1.353     | 0.936           | 0.809×0.990 | 29.1                | 1.141                      | 1.038                          | 0.971                          | 29.2        | 0.917                      | 1.042                          | 0.974                          |
| SSLT4              | Short Slot     | 2.10                | 1.700     | 1.814     | 1.901     | 0.954           | 0.803×0.992 | 35.0                | 1.041                      | 0.858                          | 0.833                          | 40.7        | 0.971                      | 1.000                          | 0.971                          |

\* Ultimate load reached prior to 1/4 in. deformation

1. Duplicate test but bolt was left untightened and plates were greased
2. Duplicate test to verify repeatability

Two linear variable differential transformers (LVDTs) were installed on the test specimen to record movement of the pull plate relative to the test plate over a 4 in. gauge length. The LVDTs recorded the bolt hole deformation as well as elastic deformations of the plates over the gauge length, however elastic deformations were minimal. An Optotrak optical tracking system was used for supplementary deformation measurements. The optical markers were installed on the test plate, pull plates, and the bolt. Measurements from the optical tracking system were used to verify the LVDT measurements as well as measure elastic elongation of the specimen and pull plate.

After applying a preload of 500 lbs to bring the connection into bearing, the test bolt was finger tightened and then brought to a snug-tight condition with a few impacts of an impact wrench. The plies were ensured to be in firm contact. All other bolts were finger tightened. The preload was released prior to applying the main load. Loading was applied in displacement control at a rate of 0.05 in/min. Most tests were stopped after a near complete loss of load-carrying capacity, typically after one or two loud sounds that likely indicated rupture. To investigate the progression of the failure mechanism, specimens labeled STD1, STD2, STD3, STD4, NC1, NC2b, and SSLT1 were stopped when a steep load drop was seen. Specimen NC2a was stopped even earlier at the first sign of any load drop. All specimens were allowed to achieve their maximum capacity.

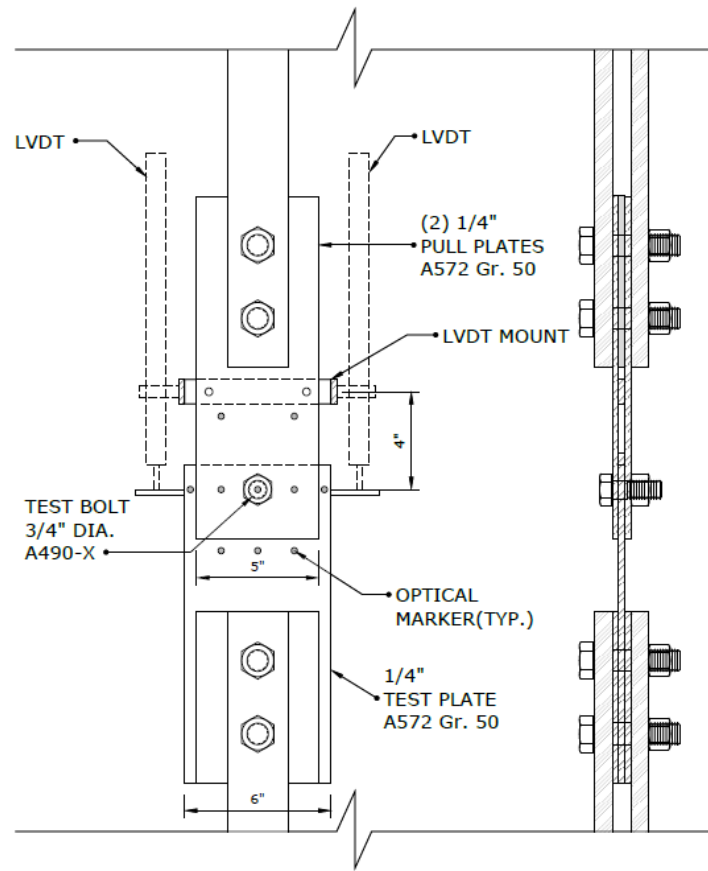


Figure 21: Experimental Test Setup

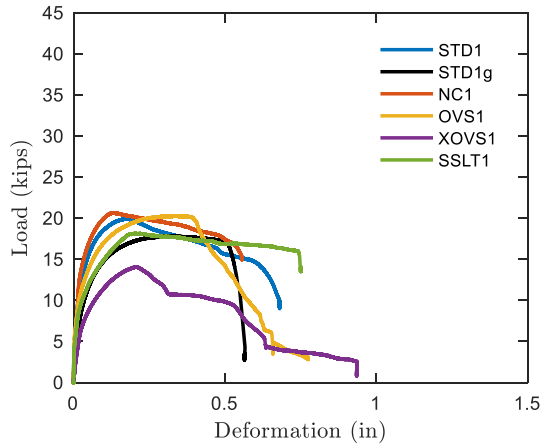
## Results

Load-deformation curves for all specimens are presented in Figure 22. The load at 1/4 in. deformation ( $R_{exp,u}$ ) and the ultimate load ( $R_{exp,u}$ ) are presented in Table 11 along with test-to-predicted using current and the proposed equations (Eqs. 15 and 16). Measured values were used in calculating the predicted strengths. For specimens with short-slotted holes,  $l_{v1}$  was computed graphically with computer-aided drafting software by drawing the specimen using measured dimensions and measuring the length from the edge of the hole to the edge of the material along lines tangent to the bolt.

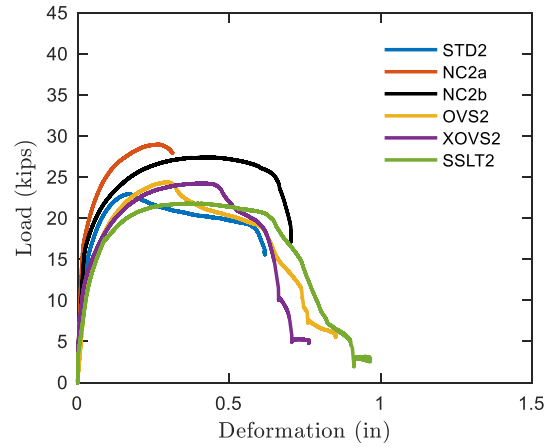
## Failure Mechanisms

Specimens were disassembled after testing to determine the failure mechanism. Upon disassembly, it was observed that most specimens had a splitting tear as well as shear rupture in the connected material along one or both sides of the bolt hole. For specimens with smaller edge distances (i.e., nominal edge distances of 1 in. and 1.25 in.), the splitting tear extended to the bolt hole, as shown in Figure 23. For specimens with larger edge distances, the split did not extend all the way to the bolt hole, as shown in Figure 24. Specimens STD4, NC4, STD1g, and NC2b did not exhibit any splitting.

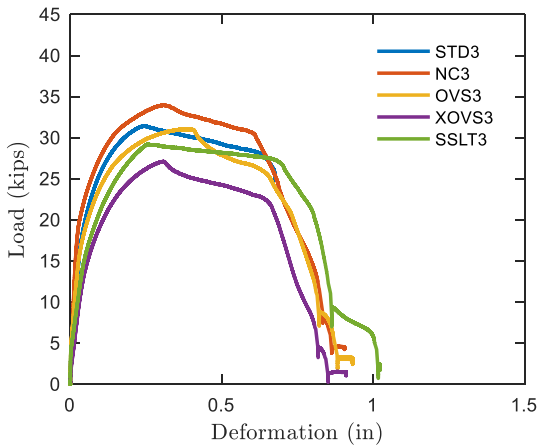
For all specimens that exhibited splitting, it is likely that the initiation of splitting occurred prior to shear rupture in the connected material and coincided with the peak load. Testing of specimen NC2a was stopped shortly after the peak load was attained. Upon disassembly, the initiation of a splitting tear was observed, but no initiation of shear rupture in the connected material was observed. Interestingly, the duplicate specimen, NC2b, did not exhibit splitting failure and achieved a 6% lower strength. The initiation



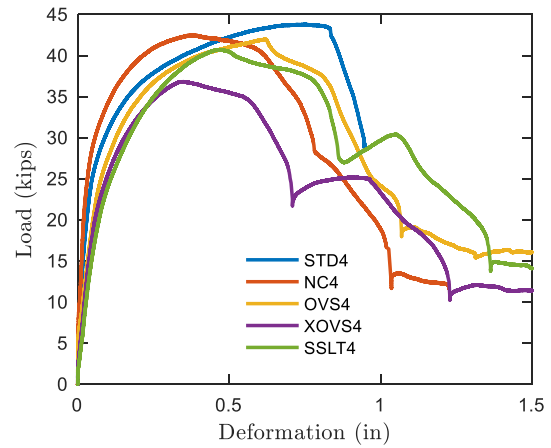
(a) Specimens with nominal edge distance of 1 in.



(b) Specimens with nominal edge distance of 1.25 in.



(b) Specimens with nominal edge distance of 1.5 in.



(b) Specimens with nominal edge distance of 2 in.

*Figure 22: Load-Deformation Curves for Experimental Tests*



*Figure 23: Photograph of specimen OVS2 after testing*



*Figure 24: Photograph of specimen OVS3 after testing*

of splitting is seen in the load-deformation curves as a dip that occurs after peak load and flattens out prior to the steeper tearout shear rupture, as depicted in Figure 23 and in Figure 24.

### **Strength Evaluation**

The means of the test-to-predicted ratios were calculated for each hole type to compare the accuracy of each tearout length, shown in Table 12 and Table 13 for the 1/4 in. deformation limit state and ultimate limit state, respectively.

The results of Table 12 and Table 13 verify the trends identified in the analysis of the previously published experiments. The current tearout equation underestimates the load at 1/4 in. deformation, which is much closer to the ultimate load than the equations imply. For load at 1/4 in. deformation, differences between the equations using  $l_{v1}$  and  $l_{v2}$  are shown to be minimal for standard and oversize holes and both were more accurate than the current equation. Across all hole types, the proposed equation with  $l_{v1}$  showed less variation but was unconservative for holes with minimal clearance. The strength of short-slotted holes was underpredicted by the equation using  $l_{v2}$ .

Frank and Yura (1981) tested four specimens with long-slotted holes oriented perpendicular to the load. They observed that the initial stiffness and load at 1/4 in. deformation was reduced when compared to standard holes but that the ultimate capacity, which was controlled by bearing for these specimens, was not reduced. As seen in Figure 22, the initial stiffness of the specimens with short-slotted holes was among the lowest of those tested in this work. However, both  $R_{exp,d}$  and  $R_{exp,u}$  were lower for the specimens with short-slotted holes than for the specimens with standard holes.

Table 12: Mean Test-to-Predicted Ratio at the 1/4 in. Deformation Limit State

| Hole Type | Using $l_c$<br>(Eq. (10)) | Using $l_{v1}$<br>(Eq. (15)) | Using $l_{v2}$<br>(Eq. (16)) |
|-----------|---------------------------|------------------------------|------------------------------|
| All       | 1.264                     | 1.008                        | 0.998                        |
| STD       | 1.293                     | 0.998                        | 1.035                        |
| NC        | 1.307                     | 0.965                        | 1.073                        |
| OVS       | 1.286                     | 1.044                        | 1.002                        |
| XOVS      | 1.272                     | 1.050                        | 0.938                        |
| SSLT      | 1.149                     | 0.994                        | 0.922                        |

Table 13: Mean Test-to-Predicted Ratio at the Ultimate Limit State

| Hole Type | Using $l_c$<br>(Eq. (10)) | Using $l_{v1}$<br>(Eq. (15)) | Using $l_{v2}$<br>(Eq. (16)) |
|-----------|---------------------------|------------------------------|------------------------------|
| All       | 1.045                     | 1.044                        | 1.032                        |
| STD       | 1.070                     | 1.034                        | 1.071                        |
| NC        | 1.065                     | 0.984                        | 1.093                        |
| OVS       | 1.078                     | 1.095                        | 1.051                        |
| XOVS      | 1.049                     | 1.085                        | 0.970                        |
| SSLT      | 0.958                     | 1.035                        | 0.961                        |

Although the mean test-to-predicted ratios for the ultimate limit state appear to be accurate for the current equation (Table 13), the results are not consistent across edge distances. This is seen by plotting the test-to-predicted ratios of all tested specimens using the current equation along with the proposed equation using  $l_{vI}$  in Figure 25.

### **Effect of Bolt Tightening**

All but one specimen was tested with the bolt installed to a snug-tight condition. The exception was specimen STD1g, which was nominally identical to STD1 but with the bolt installed loose and grease applied to the faying surfaces so as to investigate the effect of friction. The load-deformation response of specimens STD1g and STD1 is presented in Figure 26.

Several observations can be made from this pair of specimens: 1) the greased specimen was less stiff than the snug-tightened specimens; 2) the load at 1/4 in. deformation was 13% greater for the snug-tightened specimen than for the greased specimen; 3) the ultimate load was 12% greater for the snug-tightened specimen than for the greased specimen; 4) splitting was observed for the snug-tightened specimen, but not the greased specimen.

While these observations were made for a single pair of specimens, the increase in  $R_{exp,d}$  corresponds to the increase seen in previous testing data (Table 9). However, the increase in  $R_{exp,u}$  was not seen in previous testing data. Also, it is not clear why different failure modes occurred for the two specimens.

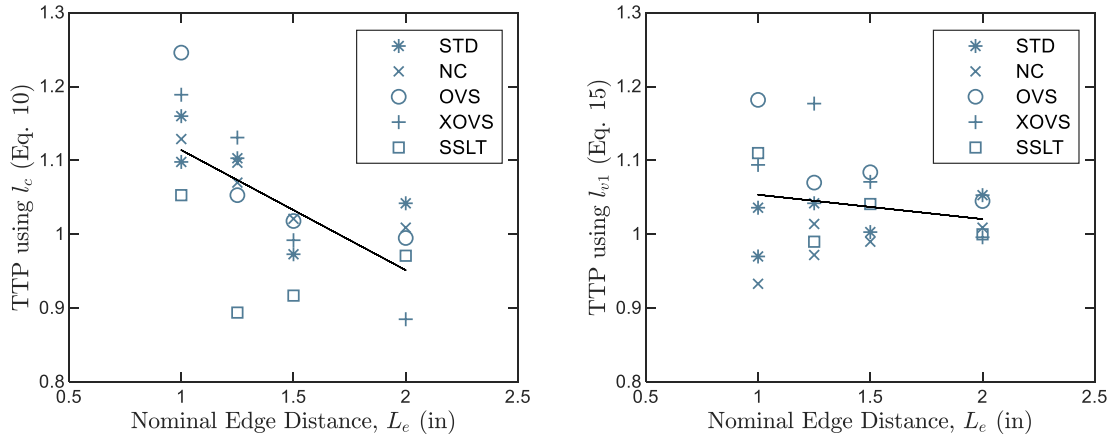


Figure 25: Test-to-Predicted Ratios at Ultimate Limit State with Best Fit Lines

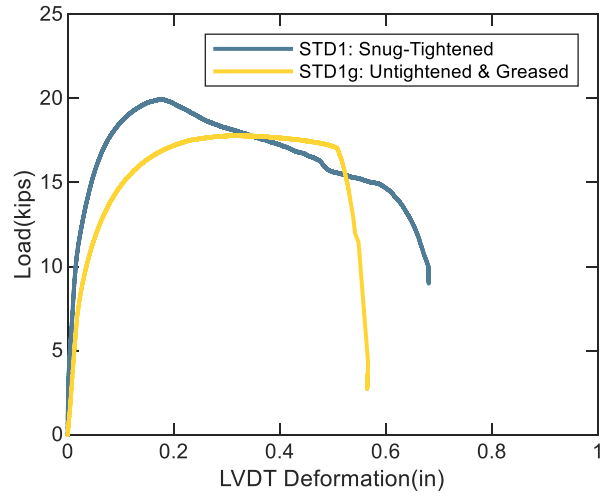


Figure 26: Snug-Tightened Specimen versus Untightened and Greased Specimen

## CHAPTER V: RELIABILITY ANALYSIS

### Overview

The Commentary on the AISC *Specification* (AISC 2016) states that the target reliability index for strength limit states is approximately 2.6 for members and 4.0 for connections. The increased target reliability for connections is due to the complexity of modeling them, sensitivity to workmanship, and the benefit that additional strength provides. Previous reliability studies on bearing and tearout in bolted connections used a first-order probabilistic method in which random variables modify the resistance calculated from design equations (Galambos 1985). In this study, noting the nonlinearity arising from multiple possible limit states, a reliability analysis was performed using Monte Carlo simulations. The objective of the reliability study was to evaluate the reliability of current and proposed design equations.

### Methodology

A limit state function,  $\tilde{g}$ , can be defined as the resistance of a particular connection,  $\tilde{R}$ , minus the load on that connection,  $\tilde{Q}$ , all three of which are assumed to be random variables (denoted with a tilde). This is presented in Eq. (17).

$$\tilde{g} = \tilde{R} - \tilde{Q} \quad (17)$$

Failure occurs when  $\tilde{Q}$  is greater than  $\tilde{R}$ , resulting in  $\tilde{g} < 0$ . The probability of failure,  $P_f$ , can be expressed as shown in Eq. (18)

$$P_f = P(\tilde{g} < 0) \quad (18)$$

The reliability index is a common method of expressing the probability of failure and is calculated in Eq. (19) as the inverse normal cumulative distribution function of the probability of failure.

$$\beta = -F_x^{-1}(P_f) \quad (19)$$

where,  $\beta$  is the reliability index and  $F_x^{-1}$  is the inverse normal cumulative distribution.

The resistance  $\tilde{R}$  should be the best approximation of the true resistance of the connection and can be determined in several ways. For use with a Monte Carlo simulation, which require many thousands of trials, code equations offer a good alternative to a finite element analysis or other means of determining the true resistance. The proposed equation using the alternative tearout length  $l_{v1}$  (Eq. 15) was used to compute resistance since this equation resulted in less variation than the current equation when compared to experimental results.

In order to focus on bearing and tearout reliabilities, and reduce the complexity of the problem, it was assumed that shear rupture of the bolt or any other limit state will not control. Therefore, the effective strength of each fastener is the minimum of the strengths computed for the limit states of bearing and tearout. Two sets of equations for  $\tilde{R}$  were formulated for each limit states, one in which deformation at service load is a design consideration and one where it is not.

Eqs. (20) through (24) apply when deformation at service load is a design consideration, denoted as the deformation limit state in this analysis.

$$\tilde{R}_d = \tilde{X}_{pd} \sum_{i=1}^n \tilde{r}_d \quad (20)$$

where  $\tilde{X}_{Pd}$  is the professional factor for the deformation limit and  $\tilde{r}_d$  is the effective strength of a fastener at the deformation limit state, computed as shown in Eqs. (21) to (24).

$$\tilde{r}_d = \tilde{r}_{d,tearout} \leq \tilde{r}_{d,bearing} \quad (21)$$

$$\tilde{r}_{d,bearing} = 2.4\tilde{d}\tilde{t}\tilde{F}_u = 2.4\left(\tilde{X}_d d_n\right)\left(\tilde{X}_t t_n\right)\left(\tilde{X}_{F_u} F_{un}\right) \quad (22)$$

For an end bolt:

$$\tilde{r}_{d,tearout} = 1.2\tilde{l}_{v1}\tilde{t}\tilde{F}_u = 1.2\left(\tilde{X}_{l_e} l_{en} - \frac{\sqrt{d_h^2 - \tilde{X}_d d_n^2}}{2}\right)\left(\tilde{X}_t t_n\right)\left(\tilde{X}_{F_u} F_{un}\right) \quad (23)$$

For an interior bolt:

$$\tilde{r}_{d,tearout} = 1.2\tilde{l}_{v1}\tilde{t}\tilde{F}_u = 1.2\left(s - \sqrt{d_h^2 - \tilde{X}_d d_n^2}\right)\left(\tilde{X}_t t_n\right)\left(\tilde{X}_{F_u} F_{un}\right) \quad (24)$$

where  $d_n$  is the nominal bolt diameter,  $d_h$  is the nominal bolt hole diameter,  $t_n$  is the nominal thickness of the connected material,  $F_{un}$  is the nominal ultimate tensile strength of the connected material,  $l_{en}$  is the nominal center-to-edge distance, and  $s$  is the center-to-center spacing of bolts. Most of the nominal values are multiplied by a corresponding random variable, denoted with a tilde, representing the ratio of the actual value to the nominal value of the variable. The random variables are described in the statistical parameters section and in Table 14.

Eq. (25) applies when deformation at service load is not a design consideration, denoted as the ultimate limit state in this analysis.

$$\tilde{R}_u = \tilde{X}_{pu} \sum_{i=1}^n \tilde{r}_u \quad (25)$$

where  $\tilde{X}_{pu}$  is the professional factor for the ultimate limit state and  $\tilde{r}_u$  is the effective strength of a fastener at the ultimate limit state, computed as shown in Eq. (26) to Eq. (28).

$$\tilde{r}_u = \tilde{r}_{u,tearout} \leq \tilde{r}_{u,bearing} \quad (26)$$

$$\tilde{r}_{u,bearing} = 3.0\tilde{d}\tilde{t}\tilde{F}_u = 3.0(\tilde{X}_d d_n)(\tilde{X}_t t_n)(\tilde{X}_{F_u} F_{un}) \quad (27)$$

For an end bolt:

$$\tilde{r}_{u,tearout} = 1.2\tilde{l}_{v1}\tilde{t}\tilde{F}_u = 1.2\left(\tilde{X}_{l_e} l_{en} - \frac{\sqrt{d_h^2 - \tilde{X}_d d_n^2}}{2}\right)(\tilde{X}_t t_n)(\tilde{X}_{F_u} F_{un}) \quad (28)$$

For an interior bolt:

$$\tilde{r}_{u,tearout} = 1.2\tilde{l}_{v1}\tilde{t}\tilde{F}_u = 1.2\left(s - \sqrt{d_h^2 - \tilde{X}_d d_n^2}\right)(\tilde{X}_t t_n)(\tilde{X}_{F_u} F_{un}) \quad (29)$$

The nominal load effect,  $\tilde{Q}$ , is equal to the sum of the dead and live load multiplied by their respective random variable, as shown in Eq. (30) through (32). Only dead and live load are considered in this study, as was done in previous reliability studies (Galambos 1983, 1985; Lundberg and Galambos 1996).

$$\tilde{Q} = \tilde{P}_D + \tilde{P}_L \quad (30)$$

$$\tilde{P}_D = \tilde{X}_D P_{Dn} \quad (31)$$

$$\tilde{P}_L = \tilde{X}_L P_{Ln} \quad (32)$$

The nominal values of dead and live load are obtained from current or trial design equations assuming that the connection was designed at the precise limit point as shown in Eq. (33).

$$\phi R_n = R_u \quad (33)$$

The load combinations under consideration are evaluated with Eq. (34).

$$R_u = \max \left( \frac{1.4P_{Dn}}{1.2P_{Dn} + 1.6P_{Ln}} \right) \quad (34)$$

### Statistical Parameters

The professional factors,  $\tilde{X}_{Pd}$  and  $\tilde{X}_{Pu}$ , account for the expected variation between the actual strength of the connection and the computed strength. Statistical parameters of the professional factor are determined through an evaluation of the test-to-predicted ratio for a number of physical experiments. The database of experimental data presented in the evaluation of published experiments was used to generate these parameters. Only tearout and bearing failures were included. In order to be included, the specimens must meet the AISC geometric requirements for edge distance and spacing, but all bolt tightening levels were included. To evaluate the test-to-predicted ratio at the deformation limit state and ultimate limit state, the experimental tests were required to have a recorded load at 1/4 in. deformation or ultimate load, respectively. The predicted strength for each specimen was computed using Eqs. (20) and (25) with the professional factor set to unity and measured values used in place of nominal values. For the 199 specimens meeting the criteria for the deformation limit state, the resulting mean of the test-to-predicted ratio was 0.98 and the resulting coefficient of variation (COV) was 0.13. For the ultimate limit state, 219 specimens met the criteria to be included. The resulting mean of the professional factor was 1.01 and the resulting COV was 0.13.

Statistical parameters for material strength ( $\tilde{X}_{F_u}$ ), thickness ( $\tilde{X}_t$ ), bolt diameter ( $\tilde{X}_d$ ), and edge distance ( $\tilde{X}_{l_e}$ ) were explicitly assigned to calculate the expected resistance. Due to large differences in the material strength and thickness between flanges of W-

sections and plates, these materials were treated separately. The parameters were derived from literature. Test-to-predicted material strengths were researched by Liu et al. (2007) for various steel strengths and shapes. From this study, data from A992 wide flange steel as well as A572 steel plates were used. The random variable for flange thickness was determined from data collected by Kennedy and Aly (1980) of 2768 measurements of flange thicknesses. The random variable for plate thickness was determined from Schmidt and Bartlett (2002) for plates used in welded wide flange plate girders. No previous research on the statistical variation of bolt diameter or bolt placement was found. The variation of bolt diameter was based on manufacturing tolerances for a heavy hex 3/4 in. diameter bolt per (ASME 2006), and assuming a 99.7% confidence interval (within three standard deviations). The probability distribution was truncated to be within the ASME tolerances, which guarantees that the bolt diameter does not exceed the hole diameter (a deterministic value). Variation of the bolt edge distance was assumed to follow a normal distribution without bias and with an 99.7% confidence that the bolt is placed within a tolerance of 1/8 in. Spacing of bolts was set as a deterministic value to account for the effect of spacing correction as bolt holes are fabricated. The random variables for dead and live load are the ones proposed by Ellingwood et al. (1980). Dead load is modeled as a normally distributed variable whereas live load is modeled as a Type I extreme value distribution. Table 14 summarizes the statistical parameters used in this reliability study.

Table 14: Summary of Statistical Parameters

| Random Variable   | Description                                                                                                           | Assumed Distribution                          |
|-------------------|-----------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| $\tilde{X}_{Pd}$  | Ratio of actual to predicted strength for bearing and tearout failures when deformation is a design consideration     | Normal<br>(mean=0.98, COV=0.13)               |
| $\tilde{X}_{Pu}$  | Ratio of actual to predicted strength for bearing and tearout failures when deformation is a not design consideration | Normal<br>(mean=1.01, COV=0.13)               |
| $\tilde{X}_{Fuf}$ | Ratio of actual to nominal ultimate tensile strength of wide flange material                                          | Normal<br>(mean=1.12, COV=0.04)               |
| $\tilde{X}_{Fup}$ | Ratio of actual to nominal ultimate tensile strength of plate material                                                | Normal<br>(mean=1.26, COV=0.07)               |
| $\tilde{X}_{tf}$  | Ratio of actual to nominal thickness of wide flange material                                                          | Normal<br>(mean=0.976, COV=0.042)             |
| $\tilde{X}_{tp}$  | Ratio of actual to nominal thickness of plate material                                                                | Normal<br>(mean=1.04, COV=0.025)              |
| $\tilde{X}_d$     | Ratio of actual to nominal bolt diameter                                                                              | Truncated Normal<br>(mean=1.00, COV=0.02)     |
| $\tilde{X}_{le}$  | Ratio of actual to nominal edge distance                                                                              | Normal<br>(mean=0.00, S.D.=0.05")             |
| $\tilde{X}_D$     | Ratio of actual to nominal dead load                                                                                  | Normal<br>(mean=1.05, COV=0.10)               |
| $\tilde{X}_L$     | Ratio of actual to nominal live load                                                                                  | Type 1 Extreme Value<br>(mean=1.00, COV=0.25) |

## Variable Sensitivity Analysis

The methodology described in the previous sections was used to run Monte Carlo simulations to compare the reliabilities of existing and alternative equations on butt spliced connections. Due to the quantity of variables to be considered in the reliability analysis, it was required to narrow the scope to the most important parameters. It was known that variables such as the number of bolts in a line parallel to load, edge distance, spacing, and ratio of the connected material thicknesses would have the most effect on reliability. Prior to excluding the remaining variables, a sensitivity analysis was performed to ensure that any further analysis would be efficient and conservative.

The ratio of the connected material thickness was selected to be 1:1, meaning that the sum of the exterior plate thicknesses was equal to the interior plate thickness. This is the most conservative approach since failure in either part is more likely occur, decreasing reliability. However, it was chosen to use the wide flange material for the interior part and plate for the exterior parts to provide a more averaged material strength. Since the wide flange material has a lower test-to-predicted ratio ultimate strength, it was more susceptible to fail.

The remaining variables are bolt diameter, material ultimate strength ( $F_u$ ), connected material thickness (while maintaining ratio), live to dead load ratio (L/D ratio), and number of bolt lines. These were hypothesized to have a minimal effect on the reliability. The first stage of the analysis was to perform a sensitivity analysis on these variables by varying them independently on a typical connection with a constant number of bolts in a line (3), edge distance ( $2d$ ), spacing ( $3d$ ), and connected material thickness ratio (1:1). Default values of bolt diameter ( $3/4$  in.), connected material ultimate strength

(65 ksi), connected material thickness (1/8 in.), L/D ratio (3), and number of bolt lines (1) were also used. For simplicity, only the current equations against the ultimate limit state were used to determine reliability for the sensitivity analysis.

It was found that only bolt diameter and the live-to-dead load ratio had any influence on reliability. Changing the connected material thickness, number of bolt lines parallel to load, and the material ultimate strength made no difference to reliability. This is because the “true” resistance and predicted resistances are both proportionally based on these variables, so reliability is not changed. The effects of changing bolt diameter and live-to-dead load ratio are shown in Table 15. As expected, the reliability decreases as the L/D ratio increases due to the additional uncertainty inherent in the live load statistical parameter. A L/D ratio of 3.0 was chosen for further analysis in this study, as it offers a realistic and conservative approach to calculating reliability and has been previously used in other studies (Galambos 1983, 1985; Lundberg and Galambos 1996). Bolt diameter has a minimal effect on reliability and 3/4 in. diameter bolts were selected for further reliability analysis in this thesis. The material selected was 1/8 in. thickness, 65 ksi ultimate strength, and contained one line of bolts.

Table 15: Sensitivity of Bolt Diameter and Live-to-Dead Load Ratio on Reliability

| Bolt Diameter | $\beta$ |
|---------------|---------|
| 5/8"          | 3.42    |
| 3/4"          | 3.41    |
| 7/8"          | 3.41    |
| 1"            | 3.44    |
| 1-1/8"        | 3.43    |
| L/D Ratio     | $\beta$ |
| 1             | 3.61    |
| 2             | 3.48    |
| 3             | 3.41    |
| 4             | 3.37    |
| 5             | 3.34    |

## Reliability Analysis and Results

After determining which variables can be maintained constant, the focus of the reliability study was narrowed to the effects of the number of bolts in a line, the edge distance, and spacing. Three combinations of edge distance and spacing were selected to generate plots of reliability versus the number of bolts in a line. Two design methods were also considered:

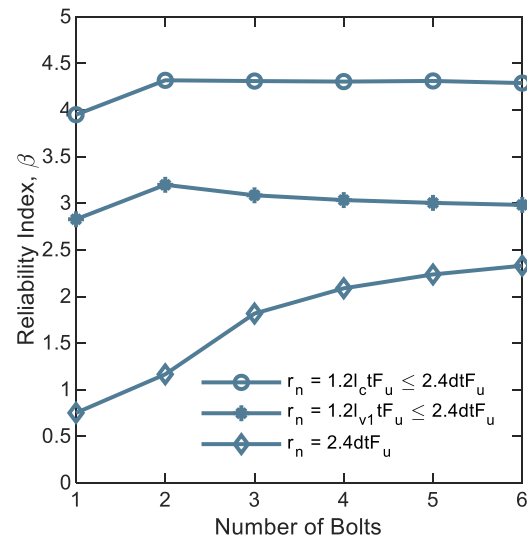
1. Deformation at bolt holes at service load is a design consideration (reliability against deformation limit state).
2. Deformation at bolt holes at service load is a not design consideration (reliability against ultimate limit state).

Each plot includes two lines indicating the current equation and proposed equation shown in Eq. (15). A third line was included to investigate the effect of ignoring tearout in the current equation. Although a certain number of bolts in a connection will negate the strength reduction of a tearout controlled edge bolt, it was expected that this would require many bolts to have a significant effect. The number of samples used in the Monte Carlo simulations was  $5 \times 10^7$ . This sample size results in a 95% confidence that the reliability index error is within  $\pm 0.0025$ .

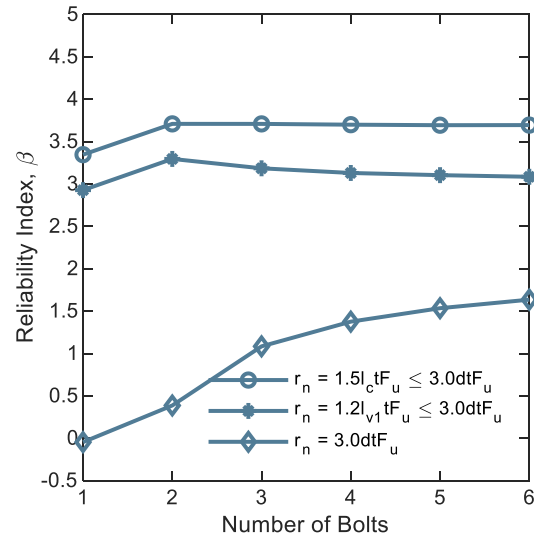
The first case, shown in Figure 27, evaluated the reliability using both minimum edge distance ( $1.33d$  for a  $3/4$  in. bolt) and minimum spacing ( $2.33d$ ). The second case, shown in Figure 28 tested an edge distance of  $2d$  and a spacing of  $4d$ , which is more representative of typical connection geometries. The third case, shown in Figure 29 was designed to fail in only bearing, with the edge distance and spacing set  $6d$  and  $12d$ ,

respectively. This provides the widest range of geometries so as to evaluate the ranges of expected reliabilities.

Figure 27 through Figure 29 demonstrate that the alternative equation using the modified tearout length provides the most consistent results ( $\beta \approx 3$ ) between different edge distances, and is also consistent between tearout and bearing-controlled cases. The reliability index of 3.0 achieved by the alternative equations is not lower than the current equation in a bearing-controlled connection and therefore appears to be acceptable. It is important to note that since the “true” resistance was determined from the alternative equation, the current design equation result in higher reliabilities for tearout since they tend to underestimate the capacity. Ignoring tearout is shown to result in a noticeable decrease in strength for cases with less than 6 bolts, even when using typical edge distance and spacing. On the basis of reliability, removing the tearout equation cannot be justified.

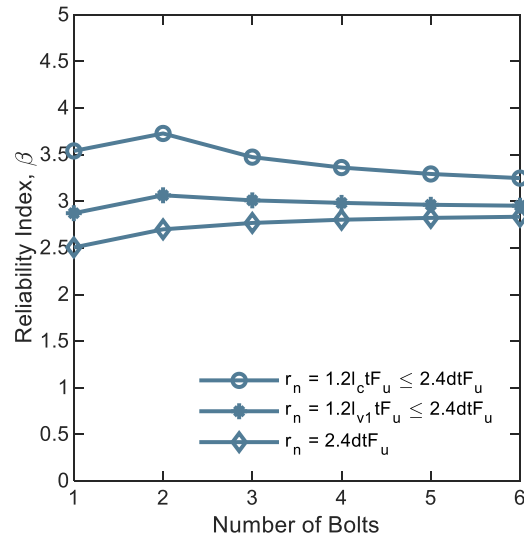


(a) Reliability against deformation limit state

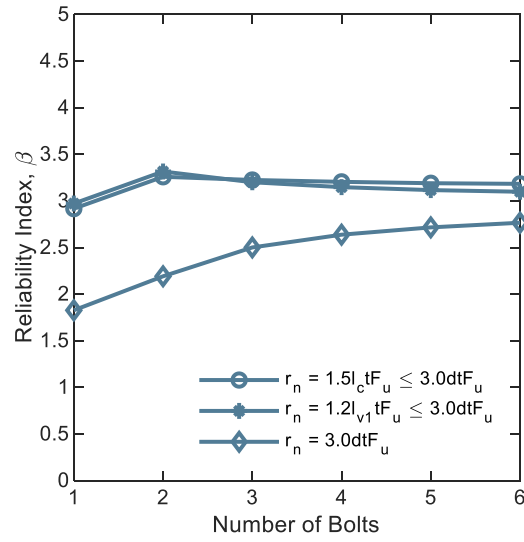


(b) Reliability against ultimate limit state

Figure 27: Reliability at Minimum Edge Distance and Spacing

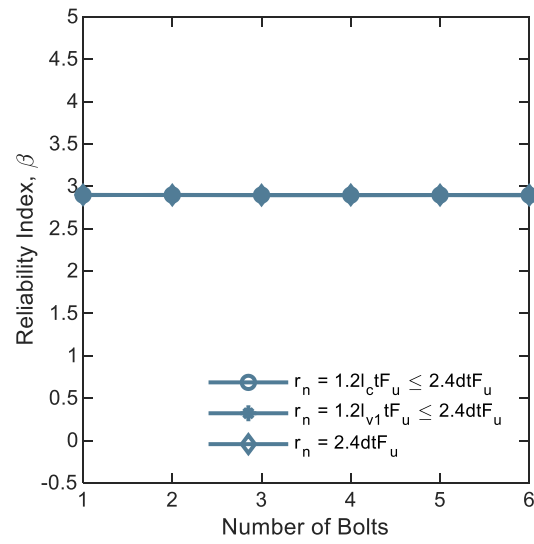


(a) Reliability against deformation limit state

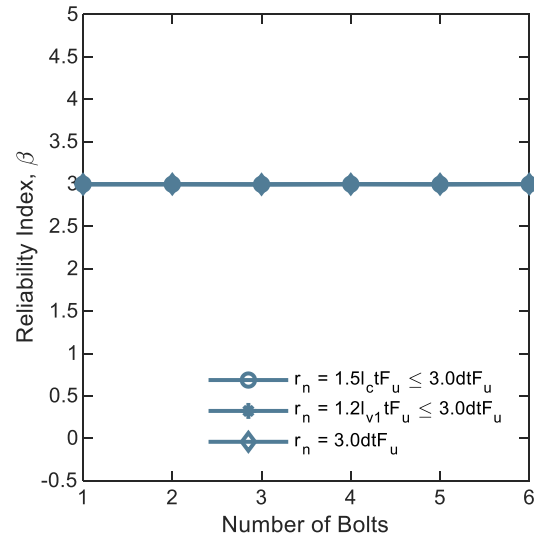


(b) Reliability against ultimate limit state

Figure 28: Reliability at Typical Edge Distance and Spacing



(a) Reliability against deformation limit state



(b) Reliability against ultimate limit state

Figure 29: Reliability at Maximum Edge Distance and Spacing

## CHAPTER VI: ALTERNATIVE DESIGN APPROACH

### Overview

The proposed equations provide improved accuracy over current equations. However, there remains the possibility of different effective strengths for bolts within a group. These different strengths represent physical behavior, but they can be inconvenient for design. It may be convenient to have a uniform effective strength among bolts in a group for design, even if such an evaluation was conservative. In this section, an alternative design approach, or rule-of-thumb, where tearout need not be checked directly and the strength of each bolt within a group can be taken as the same will be developed. For this approach, reduction factors are applied to the bearing and bolt shear rupture strength such that the tearout limit state need not be checked explicitly.

### Derivation of the Approach

The strength equations for the limit states of bearing and tearout are similar in that they both include the term  $tF_u$ . Accordingly, the ratio between the strength for the two limit states depends only on the bolt diameter,  $d$ , and the clear distance,  $l_c$ . For the case when deformation at the bolt hole at service load is a design consideration, the ratio of nominal strength for the limit state of tearout for an individual bolt,  $r_{nt}$ , to the nominal strength for the limit state of bearing for an individual bolt,  $r_{nb}$ , is equal to  $l_c/2d$ . This ratio is calculated for a range of bolt diameters and for both standard and oversize holes in Table 16 and Table 17. In Table 16, it is assumed that the bolt is adjacent to an edge and the minimum edge distance per Section J3.4 of the AISC *Specification* is provided. In Table 17, it is assumed that the bolt is adjacent to another bolt and a spacing of  $3d$  (as recommended in Section J3.3 of the AISC *Specification*) is provided. From these tables it can be concluded that, for

Table 16: Ratio of tearout strength to bearing strength for edge bolts

| $d$<br><i>in</i> | Standard Holes     |                          |                          |                            | Oversize Holes     |                          |                          |                            |
|------------------|--------------------|--------------------------|--------------------------|----------------------------|--------------------|--------------------------|--------------------------|----------------------------|
|                  | $d_h$<br><i>in</i> | $L_{e,min}$<br><i>in</i> | $l_{c,min}$<br><i>in</i> | $r_{nt,min}/r_{nb}$<br>--- | $d_h$<br><i>in</i> | $L_{e,min}$<br><i>in</i> | $l_{c,min}$<br><i>in</i> | $r_{nt,min}/r_{nb}$<br>--- |
| 1/2              | 0.563              | 0.750                    | 0.469                    | 0.469                      | 0.625              | 0.813                    | 0.500                    | 0.500                      |
| 5/8              | 0.688              | 0.875                    | 0.531                    | 0.425                      | 0.813              | 0.938                    | 0.531                    | 0.425                      |
| 3/4              | 0.813              | 1.000                    | 0.594                    | 0.396                      | 0.938              | 1.063                    | 0.594                    | 0.396                      |
| 7/8              | 0.938              | 1.125                    | 0.656                    | 0.375                      | 1.063              | 1.188                    | 0.656                    | 0.375                      |
| 1                | 1.125              | 1.250                    | 0.688                    | 0.344                      | 1.250              | 1.375                    | 0.750                    | 0.375                      |
| 1 1/8            | 1.250              | 1.500                    | 0.875                    | 0.389                      | 1.438              | 1.625                    | 0.906                    | 0.403                      |
| 1 1/4            | 1.375              | 1.625                    | 0.938                    | 0.375                      | 1.563              | 1.750                    | 0.969                    | 0.388                      |
| 1 3/8            | 1.500              | 1.719                    | 0.969                    | 0.352                      | 1.688              | 1.844                    | 1.000                    | 0.364                      |
| 1 1/2            | 1.625              | 1.875                    | 1.063                    | 0.354                      | 1.813              | 2.000                    | 1.094                    | 0.365                      |

Table 17: Ratio of tearout strength to bearing strength for interior bolts

| $d$<br><i>in</i> | Standard Holes     |                   |                         |                           | Oversize Holes     |                   |                         |                           |
|------------------|--------------------|-------------------|-------------------------|---------------------------|--------------------|-------------------|-------------------------|---------------------------|
|                  | $d_h$<br><i>in</i> | $3d$<br><i>in</i> | $l_{c,3d}$<br><i>in</i> | $r_{nt,3d}/r_{nb}$<br>--- | $d_h$<br><i>in</i> | $3d$<br><i>in</i> | $l_{c,3d}$<br><i>in</i> | $r_{nt,3d}/r_{nb}$<br>--- |
| 1/2              | 0.563              | 1.500             | 0.938                   | 0.938                     | 0.625              | 1.500             | 0.875                   | 0.875                     |
| 5/8              | 0.688              | 1.875             | 1.188                   | 0.950                     | 0.813              | 1.875             | 1.063                   | 0.850                     |
| 3/4              | 0.813              | 2.250             | 1.438                   | 0.958                     | 0.938              | 2.250             | 1.313                   | 0.875                     |
| 7/8              | 0.938              | 2.625             | 1.688                   | 0.964                     | 1.063              | 2.625             | 1.563                   | 0.893                     |
| 1                | 1.125              | 3.000             | 1.875                   | 0.938                     | 1.250              | 3.000             | 1.750                   | 0.875                     |
| 1 1/8            | 1.250              | 3.375             | 2.125                   | 0.944                     | 1.438              | 3.375             | 1.938                   | 0.861                     |
| 1 1/4            | 1.375              | 3.750             | 2.375                   | 0.950                     | 1.563              | 3.750             | 2.188                   | 0.875                     |
| 1 3/8            | 1.500              | 4.125             | 2.625                   | 0.955                     | 1.688              | 4.125             | 2.438                   | 0.886                     |
| 1 1/2            | 1.625              | 4.500             | 2.875                   | 0.958                     | 1.813              | 4.500             | 2.688                   | 0.896                     |

the conditions considered, the tearout strength of an edge bolt is no less than 0.344 times its bearing strength (Eq. 35) and the tearout strength of an interior bolt is no less than 0.850 times its bearing strength (Eq. 36).

$$r_{nt} \geq \alpha r_{nb} = 0.344 r_{nb} \quad (35)$$

$$r_{nt} \geq \beta r_{nb} = 0.850 r_{nb} \quad (36)$$

where,  $\alpha$  and  $\beta$  are minimum strength ratios determined from Table 16 and Table 17, respectively (i.e.,  $\alpha = 0.344$  and  $\beta = 0.850$ ).

Consider the generic connection shown in Figure 30. The strength of the bolt group is the summation of the effective strength of each of the bolts. Assuming that shear rupture of the bolt does not control the effective strength of any of the bolts, then the lower bound of the strength of the bolt group can be computed as shown in Eq. (37), noting that there are two bolts adjacent to edges and the remaining bolts are interior.

$$R_n \geq 2\alpha r_{nb} + (n-2)\beta r_{nb} \quad (37)$$

where  $n$  is the total number of bolts in the line. Rearranging terms results in Eq. (38):

$$R_n \geq n \left( \frac{2\alpha + (n-2)\beta}{n} \right) r_{nb} = n x_b r_{nb} \quad (38)$$

where,  $x_b$  is a reduction factor applied to the bearing strength.

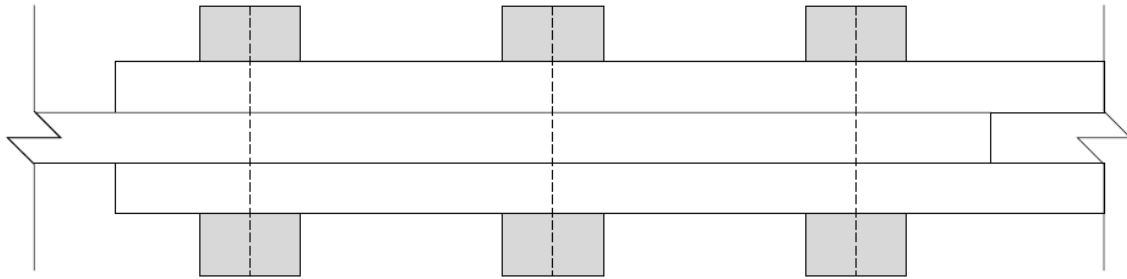


*Figure 30: Example Connection for the Alternative Design Method*

According to Eq. (38), a lower-bound estimate of the strength of a bolt group can be obtained as the number of bolts times a reduced bearing strength. The reduction factor is given by Eq. (39):

$$x_b = \frac{2\alpha + (n-2)\beta}{n} \approx 0.85 - \frac{1}{n} \quad (39)$$

However, bolt shear rupture strength may not be neglected in general. A similar reduction factor applied to the bolt shear rupture strength,  $r_{ns}$ , can be determined to address cases where bolt shear rupture and tearout control the effective strength of the various individual bolts. In such a case, a lower-bound estimate of the strength can be computed as Eq. (40).

$$R_n \geq nx_s r_{ns} = 2\alpha r_{nb} + (n-2)r_{ns} \quad (40)$$

The maximum necessary reduction will occur when the bolt shear rupture strength is equal to the reduced bearing strength for the interior bolts ( $r_{ns} = \beta r_{nb}$ ):

$$R_n \geq nx_s \beta r_{nb} = 2\alpha r_{nb} + (n-2)\beta r_{nb} \quad (41)$$

Solving for  $x_s$ :

$$x_s = \frac{2\alpha + (n-2)\beta}{n\beta} \approx 1 - \frac{1}{0.85n} \quad (42)$$

Accordingly, a lower-bound estimate of the strength of a concentrically loaded bolt group, can be determined using Eq. (43) without the need to directly evaluate the limit state of tearout.

$$R_n \geq n \min(x_b r_{nb}, x_s r_{ns}) \quad (43)$$

This equation, with  $x_b$  defined by Eq. (39) and  $x_s$  defined by Eq. (42), is applicable to when deformation at the bolt hole at service load is a design consideration, standard or oversize holes are used, the minimum required edge distances are met, spacing greater than or equal to  $3d$  is provided, and strength is computed according to the 2016 AISC *Specification* (i.e., not the proposed equations in this work). However, within these conditions, Equation 43 applies to any number of bolts, bolt diameter, and bolt grade. Alternative reduction factors for different situations and ranges of parameters can be computed using different values of  $\alpha$  and  $\beta$ . If edge distances and spacings are large enough, then tearout does not control and the reduction factors are no longer necessary. With current AISC equations, this would occur when the clear distance is greater than  $2d$ .

## CONCLUSIONS AND RECOMMENDATIONS

A multifaceted investigation of the limit state of tearout and its impact on design of steel bolted connections has been conducted. Previously published experimental data was evaluated and supplemented with new experimental data to assess the accuracy of current provisions as well as potential alternative provisions.

This study has shown that increased accuracy in design can be achieved by replacing Equations J3-6c and J3-6d in the AISC *Specification* with Eq. (44).

$$R_n = 1.2l_{v1}tF_u \quad (44)$$

This proposed equation is shown in terms of  $l_{v1}$ , since it provides somewhat better results over a wider range of types of bolt holes, particularly short-slotted holes. However, the same equation but with  $l_{v2}$  in lieu of  $l_{v1}$  would provide similar benefits. The reliability of Eq. (44) has been shown to be at a suitable level and consistent across different parameters, including number of bolts and edge distance.

While Eq. (44) provides increased accuracy over current equations, the computation of the alternative tearout lengths is somewhat more complicated than the computation of the clear distance. This is especially true for eccentrically loaded bolt groups which are not covered in this work, but pose a challenge since the direction of force varies from bolt to bolt. Neither of the alternative tearout lengths are well defined nor have they been validated for loads at an angle. Additional development and validation is necessary for eccentrically loaded connections.

The following additional conclusions can be made from this work:

- Tearout impacts the strength of bolt groups, even for cases of multiple bolts in a row.
- The current equation for tearout strength when deformation at the bolt hole at service load is a design consideration (i.e., load at 1/4 in. deformation) is conservative, especially for shorter edge distances. On average, the current equation underestimates the experimental strength by 20-25%.
- Ultimate load for the limit state of tearout is approximately 5% larger than the load at 1/4 in. deformation, significantly less than the 25% implied by current provisions.
- Bolt tightening increases the load at 1/4 in. deformation by an average of 8% for a pretensioned bolt condition over an untightened bolt condition. No clear effect of bolt tightening was found at the ultimate load.
- Two alternative tearout lengths,  $l_{v1}$  and  $l_{v2}$ , were investigated for their potential to improve the accuracy of design equations. Strength equations using these alternative tearout lengths were found to be more accurate than the current equations which use the clear distance,  $l_c$ , with a mean test-to-predicted ratio closer to 1.00 and a smaller coefficient of variation for all examined cases.
- Design equations with  $l_{v1}$  and  $l_{v2}$  are similarly accurate for connections with standard and oversize holes. The design equation using  $l_{v2}$  was found to be somewhat unconservative for short-slotted holes and hole with clearance

greater than oversize. The design equation using  $l_{v1}$  was found to be accurate of the entire range of hole types investigated.

- The alternative provisions provide a sufficient and consistent level of reliability across a wide range of parameters.
- An alternative design method in which reduction factors are used on bearing and bolt shear rupture strength was developed. The method allows the tearout check to be removed by reducing strength, which can be beneficial in some design cases.

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## **VITA**

Nicolo Franceschetti was born in Denver, Colorado to Alberto Franceschetti and Paola Verzoni. He attended Bearden High School in Knoxville, Tennessee. He began studying at the University of Tennessee, Knoxville in 2014 and graduated with a B.S. in Civil Engineering in December 2017. He remained at the University of Tennessee to pursue a M.S. in Civil Engineering with a concentration in Structural Engineering. He plans to have a professional career as a structural engineer in industry.