High Fidelity Modeling of Cold-Formed Steel Single Lap Shear Screw Fastened Connections

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High Fidelity Modeling of Cold-Formed Steel Single Lap Shear Screw Fastened Connections

A Thesis Presented

by

RITA KALO

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

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Civil Engineering
HIGH FIDELITY MODELING OF COLD-FORMED STEEL SINGLE LAP SHEAR SCREW FASTENED CONNECTIONS

A Thesis Presented

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Approved as to style and content by:

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ACKNOWLEDGEMENTS

My advisor, Dr. Peterman is the reason I am writing this thesis today. I want to thank you for introducing me to the world of cold-formed steel, and always being available to help guide me to the right path whenever I had trouble with my research or was discouraged by my results.

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ABSTRACT

HIGH FIDELITY MODELING OF COLD-FORMED STEEL SINGLE LAP SHEAR SCREW FASTENED CONNECTIONS

FEBRUARY 2019

RITA KALO, B.S., UNIVERSITY OF FLORIDA
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Cold-formed steel connections are commonly fastened using self-tapping self-drilling screws. The behavior of these connections can differ based on the screw manufacturer or the cold-formed steel product used, both of which have a large selection available for use in industry. Because of their popularity and the many possible variations of these connections, researchers have frequently tested screw connections to characterize their behavior. However, repeatedly conducting this type of experiment is time consuming and expensive. Therefore, the purpose of this work was to create finite element models that can successfully predict the behavior of single lap shear screw connections, a common connection type used in cold-formed steel framing. These models were created using the finite element program Abaqus/CAE. To validate these models, test results from Pham and Moen (2015) were used to compare the stiffness, strength, and failure mode of multiple connections. A parametric study is also conducted to determine the influence of contact parameters on the behavior of the model.

The results showed that all models consistently had good agreement with the connection stiffness and that most of the models also had good agreement with the peak load and failure mode of the
tests. These results were also compared to the design equations available for screw connections from the American Iron and Steel Institute (AISI). This comparison revealed that the models are more successful at predicting screw connection behavior than AISI, and thus work is required to improve the accuracy of AISI’s design equations. The eventual goal of this work is to develop a procedure to build and validate models without requiring test data. This work continuing in the future can lead to recommendations to improve AISI’s design equations and to implement the behavior of the connections into large cold-formed steel framing models such as diaphragms or shear walls.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Hot rolled steel finite element modeling in literature</td>
<td>2</td>
</tr>
<tr>
<td>1.2. Cold formed steel connections in literature</td>
<td>3</td>
</tr>
<tr>
<td>2. REVIEW OF THE LITERATURE</td>
<td>6</td>
</tr>
<tr>
<td>3. EXISTING EXPERIMENT INFORMATION</td>
<td>8</td>
</tr>
<tr>
<td>3.1. Test Setup</td>
<td>8</td>
</tr>
<tr>
<td>3.2. Tests Modeled</td>
<td>10</td>
</tr>
<tr>
<td>4. FINITE ELEMENT MODEL</td>
<td>12</td>
</tr>
<tr>
<td>4.1. Finite element analysis product</td>
<td>12</td>
</tr>
<tr>
<td>4.2. Model Setup</td>
<td>12</td>
</tr>
<tr>
<td>4.2.1. Screw Modeling</td>
<td>12</td>
</tr>
<tr>
<td>4.2.2. Ply Modeling</td>
<td>13</td>
</tr>
<tr>
<td>4.3. Screw Material Properties</td>
<td>15</td>
</tr>
<tr>
<td>4.4. Ply Material Properties</td>
<td>17</td>
</tr>
</tbody>
</table>
4.5. Boundary conditions ................................................................. 18

4.6. Contact Definitions ................................................................. 22

  4.6.1. Tangential Contact Definitions ........................................... 22

  4.6.2. Normal Contact Definitions .............................................. 23

4.7. Mesh details ............................................................................. 27

4.8. Failure Criteria ......................................................................... 29

  4.8.1. Failure Modes .................................................................... 29

  4.8.2. Screw Shear and Screw Tilting Failure Criteria .................... 30

  4.8.3. Ply Failure Criteria ........................................................... 31

  4.8.4. Combination Failure Criteria ............................................ 32

5. RESULTS AND DISCUSSION ......................................................... 34

5.1. Results ...................................................................................... 34

  5.1.1. Failure Mode ..................................................................... 34

    5.1.1.1. Screw Tilting and Bearing: Same Ply 1 and 2 Thickness .... 34

    5.1.1.2. Screw Tilting and Bearing: Different Ply 1 and Ply 2 Thickness .... 38

    5.1.1.3. Screw Shear: Same Ply 1 and Ply 2 Thickness .................. 42

    5.1.1.4. Screw Shear: Different Ply 1 and Ply 2 Thickness ............... 45

  5.1.2. Peak Load and Stiffness in Tests vs Model ......................... 50

    5.1.2.1. Screw Tilting and Bearing: Same Ply 1 and Ply 2 Thickness .... 50

    5.1.2.2. Screw Tilting and Bearing: Different Ply 1 and Ply 2 Thickness .... 53

    5.1.2.3. Screw Shear: Same Ply 1 and Ply 2 Thickness .................. 58

    5.1.2.4. Screw Shear: Different Ply 1 and Ply 2 Thickness ............... 60
5.2. Parametric study of contact properties used to create robust model ........................................ 66

5.2.1. Maximum Contact Stiffness ........................................................................................................ 66

5.2.2. Initial Contact Stiffness .............................................................................................................. 70

5.2.3. Lower and Upper Quadratic Limits ........................................................................................... 71

5.3. Comparison of model and test results to AISI ............................................................................. 74

5.4. Future Work ................................................................................................................................... 78

5.4.1. Failure Modes ............................................................................................................................. 79

5.4.2. Peak Load .................................................................................................................................... 80

5.4.3. Connection Stiffness .................................................................................................................. 81

5.4.4. Modeling Improvements ............................................................................................................ 82

6. CONCLUSION .................................................................................................................................... 86

REFERENCES ......................................................................................................................................... 88
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1: Model Matrix</td>
<td>11</td>
</tr>
<tr>
<td>Table 2: Ply Material Properties (Tao and Moen 2017)</td>
<td>17</td>
</tr>
<tr>
<td>Table 3: Nonlinear penalty parameters used for each model</td>
<td>27</td>
</tr>
<tr>
<td>Table 4: Model and test stiffness comparison for 3333 ply configuration</td>
<td>51</td>
</tr>
<tr>
<td>Table 5: Model and test stiffness comparison for 4343 ply configuration</td>
<td>53</td>
</tr>
<tr>
<td>Table 6: Model and test stiffness comparison for 3368 ply configuration</td>
<td>54</td>
</tr>
<tr>
<td>Table 7: Model and stiffness comparison for 4354 ply configuration</td>
<td>57</td>
</tr>
<tr>
<td>Table 8: Model and test stiffness comparison for 4368 ply configuration</td>
<td>57</td>
</tr>
<tr>
<td>Table 9: Model and test stiffness comparison for 5454 ply configuration</td>
<td>59</td>
</tr>
<tr>
<td>Table 10: Model and test stiffness comparison for 4397 ply configuration</td>
<td>61</td>
</tr>
<tr>
<td>Table 11: Model and test stiffness comparison for 6843 ply configuration</td>
<td>63</td>
</tr>
<tr>
<td>Table 12: Model and test stiffness comparison for 9733 ply configuration</td>
<td>65</td>
</tr>
<tr>
<td>Table 13: Model and test stiffness comparison for 9797 ply configuration</td>
<td>84</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1: Schematic of test setup (Corner 2014)</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2: Schematic of test measurement setup (Pham and Moen 2015)</td>
<td>10</td>
</tr>
<tr>
<td>Figure 3: Image of screw used in model (left) vs. Simpson X Screw (ICC 2018) (right) used in tests</td>
<td>13</td>
</tr>
<tr>
<td>Figure 4: Relative displacement measurement points used in model</td>
<td>14</td>
</tr>
<tr>
<td>Figure 5: Typical image of models and locations of aluminum fixture boundary conditions on model</td>
<td>15</td>
</tr>
<tr>
<td>Figure 6: Boundary condition fixing upward motion on Ply 2</td>
<td>19</td>
</tr>
<tr>
<td>Figure 7: Boundary condition on edges of both plies (front view of model)</td>
<td>20</td>
</tr>
<tr>
<td>Figure 8: Boundary conditions restraining out of plane motion. Left: Front of model. Right: Back of model</td>
<td>21</td>
</tr>
<tr>
<td>Figure 9: Loading protocol of model and Pham and Moen (2015) tests</td>
<td>22</td>
</tr>
<tr>
<td>Figure 10: Nonlinear penalty contact behavior in Abaqus (Abaqus User’s Guide 2014)</td>
<td>25</td>
</tr>
<tr>
<td>Figure 11: a) Overall ply mesh b) Elements in thickness on edge of ply c) Detail of mesh at hole</td>
<td>28</td>
</tr>
<tr>
<td>Figure 12: Typical screw mesh</td>
<td>29</td>
</tr>
<tr>
<td>Figure 13: Model failing by screw shear</td>
<td>30</td>
</tr>
<tr>
<td>Figure 14: Undeformed view of screw in model failing by screw shear, shown by line of yielded elements</td>
<td>31</td>
</tr>
<tr>
<td>Figure 15: 3333 model a) Ovalization of ply 1 hole b) Minor ovalization of ply 2 hole c) Screw tilting and ply separation</td>
<td>35</td>
</tr>
</tbody>
</table>
Figure 16: Photos of 3333 test from Corner (2014) a) Screw head tilting in ply 1 b) screw shank in ply 1 c) ovalization of ply 2 hole ................................................................. 36

Figure 17: 4343 model a) Ply 1 bearing b) Ply 2 slight hole bearing c) Screw tilting and ply separation ........................................................................................................ 37

Figure 18: Photo of 4343 test from Corner (2014) a) Screw head tilting in ply 1 b) screw shank in ply 1 c) ovalization and bearing of ply 2 hole ................................................................. 37

Figure 19: 3368 model at peak load with a) Ply 1 (33 mils) under bearing b) Ply 2 (68 mils) with bearing at top of hole c) Overall connection ................................................................. 39

Figure 20: 3368 test (Corner 2014) a) Ply 1 hole tearing b) Screw head in ply 2 after ply 1 tearing c) screw shank in ply 2 ........................................................................................................ 39

Figure 21: 4354 test (Corner 2014) a) Ply 1 bearing and head tilting b) Screw shank in ply 1 c) Ply 2 hole bearing ........................................................................................................ 40

Figure 22: 4354 model a) Ply 1 bearing and ovalization b) Ply 2 deformation at top of hole c) Fastener tilting and ply separation ........................................................................................................ 41

Figure 23: 4368 model a) Ply 1 bearing and ovalization b) Ply 2 deformation at top of hole c) Fastener tilting and ply separation ........................................................................................................ 42

Figure 24: 5454 test (Corner 2014) a) Tilted screw head b) Broken screw in ply 1 c) Broken screw in ply 2 ........................................................................................................ 43

Figure 25: 5454 model: elements with Von Mises stress greater than 630 MPa ........................................................................................................ 43

Figure 26: 9797 model failing in shear ........................................................................................................ 44

Figure 27: 9797 test (Corner 2014) a) Screw head after failure b) Sheared off screw in ply 1 c) Screw shank in ply 2 after failure ........................................................................................................ 45
Figure 28: 9733 test (Corner 2014), with similar results in 4397 test a) Sheared off screw b) Ply 2 ovalization c) Folding of ply 2 and bearing ................................................................. 46
Figure 29: 9733 model a) Yield/failure line of screw b) bearing failure in ply 2 c) Overall model ........................................................................................................................................ 47
Figure 30: 4397 model at peak load a) Ply 1 bearing failure b) Ply 2 c) Screw shear and ply 1 bearing .................................................................................................................................. 48
Figure 31: 6843 model at peak load a) Ply 1 b) Ply 2 bearing failure at top of hole c) Screw shear and ply 2 bearing .................................................................................................................................. 49
Figure 32: 6843 test (Corner 2014) a) Sheared off screw in ply 1 b) Screw shank in ply 2 after failure c) Screw after failure in ply 2 .................................................................................................................................. 49
Figure 33: Pham and Moen stiffness characterization (2015) ................................................................................................................................. 50
Figure 34: 3333 Model vs Test Results ................................................................................................................................................................. 51
Figure 35: 4343 Model vs Test Results ................................................................................................................................................................. 52
Figure 36: 3368 model vs test results ................................................................................................................................................................. 54
Figure 37: 4354 model vs test results ................................................................................................................................................................. 56
Figure 38: 4368 model vs results ................................................................................................................................................................. 58
Figure 39: 5454 model vs test results ................................................................................................................................................................. 59
Figure 40: 4397 model results vs test results ................................................................................................................................................................. 61
Figure 41: 6843 model vs test results ................................................................................................................................................................. 63
Figure 42: 9733 model results vs test results ................................................................................................................................................................. 65
Figure 43: Comparison of length of run with an increase to $K_f$ for 4343 model ................................................................................................. 67
Figure 44: Comparison of peak load with increase to $K_f$ for 4343 model ................................................................................................. 68
Figure 45: Comparison of connection stiffness with increase to $K_f$ for 4343 model ................................................................................................. 69
Figure 46: Comparison of connection stiffness with increase to $K_i$ for 4343 model .................. 70
Figure 47: Comparison of effect of upper quadratic limit on 4343 model ............................. 73
Figure 48: Comparison of effect of lower quadratic limit on 4343 model ............................. 74
Figure 49: 9797 model results vs test results ........................................................................... 84
CHAPTER 1

INTRODUCTION

Connections have a large role in structural design. An incorrectly designed or constructed connection can result in dangerous failures in a structure. To ensure these connections are understood, much research has been conducted to understand the behavior of connections in structural design. Most of the research on connections for many decades was on hot-rolled structural steel connections, which have had published design recommendations for bolted connections since 1951.

Though all bolted connections tend to share some similarities, there are key differences between hot rolled steel and cold-formed steel. These differences cause many parts of hot rolled steel connection specifications to not apply to cold-formed steel connections. For example, cold-formed steel is significantly thinner than hot rolled steel, which results in another form of connection failure – fastener tilting. Also, although hot rolled steel is now connected primarily with bolts and welds, cold-formed steel connections are bolted, welded, or fastened using screws. The differences in cold-formed steel compared to hot rolled steel require dedicated research to be conducted into the behavior of cold-formed steel connections. This research did not begin until Winter’s work on bolted cold-formed steel connections in 1956. Screw-fastened connections, which are commonly used in cold-formed steel structures, did not have design recommendations in the cold-formed steel specifications until the work of Pekoz in 1990, more than three decades after the first design recommendation for hot rolled steel bolted connections was published.

The very recent inclusion of screw-fastened connections into the American Iron and Steel Institute (AISI) specification for cold-formed steel indicates that the research into cold-formed
steel connections is still limited when compared to hot rolled steel. The research conducted in this thesis aims to add to the available literature on cold-formed steel connections. As of now, finite element modeling of screw fastened cold-formed steel connections have only featured as components of larger cold-formed steel models where the screw fasteners are characterized by line elements. The information on the screw behavior used to characterize the line elements is found through experimental data. With the research conducted in this thesis, the eventual goal is for the characterization of screws in larger models to feature connection properties based on another finite element model, rather than requiring experimental data.

In order to determine what research in the literature pertains to the goal of this thesis, a literature review on connections is required. The large amount of available work on high fidelity modeling of hot-rolled steel connections is necessary to examine to develop a starting point for the finite element modeling conducted in this research. Because this thesis is specifically on cold-formed steel connections, the literature review must also feature the results of test data for screw fastened cold-formed steel connections, and any finite element modeling of cold-formed steel connections available. This literature review begins in the following section.

1.1. Hot rolled steel finite element modeling in literature
Many finite element models of bolted connections have been created for hot rolled steel. Ju, Fan and Wu (2004) explored slip critical connections and incorporated cracks into their model, comparing their results to AISC design equations. Kim, Yoon, and Kang (2007) presented different types of finite element models of connections. Their paper discussed the accuracy of modeling a solid element bolt, a coupled bolt (where bolt stud is modeled by a beam element coupled to the nodes corresponding to the nut and bolt head), a spider bolt (where the bolt stud, head, and nut are modeled by beam elements), and a “no bolt” model where the bolt is replaced
by a series of loads. Kim Yoon and Kang concluded that despite losing the ability to save computational time, the solid element bolt model yields the most accurate results.

The behavior of moment resisting connections has been one of significant interest amongst many hot rolled steel researchers. Moment resisting connections designed as T-stub models have been discussed by many, such as: Girão Coelho et. al (2006) and Gantes and Lemonis (2003).

Moment resisting connections created using end plates welded to beams and bolted to columns is a notable feature of the literature. Exploration into both 2D and 3D finite element models of end plate connections began with Krishnamurthy and Graddy (1976), and further research into 2D models of these connections was also conducted by Bahaari and Sherbourne (1993). Finite element models of moment resisting end plate connections were made by Popov et. al (2002), Bursi and Jaspart (1997), Maggi et. al (2004), Shi et. al (2008) and many others. Calibration of these models based on experimental results was also discussed by Bursi and Jaspart, Maggi et. al (2005), and Girão Coelho et. al (2006).

1.2. Cold formed steel connections in literature
The literature features many tests that describe the behavior of cold-formed steel (CFS) connections. Work by Winter (1956) and others began the development of design equations based on experimental results for connections, eventually leading to AISI and other CFS design codes. Pekoz (1990) continued this work with a series of tests on screw fastened CFS connections.

Pham and Moen (2015) and Tao, Chatterjee, and Moen (2017) both tested a series of single lap shear screw connections that are fastened using only one screw. Pham and Moen’s series of tests varied by the screw size and the thicknesses of the CFS plies connected. The stiffness of these connections was also characterized. Corner (2014) used Pham and Moen’s tests to examine how
fastener tilting affects the peak load of screw connections that use a #10 size screw. Tao, Chatterjee, and Moen (2017), which will from now on be referred to as Tao and Moen (2017), tested a series of cold-formed steel-to-steel connections and steel-to-sheathing connections under monotonic and cyclic loading. Tao and Moen’s tests featured different screw sizes, screw head types, and different thicknesses of the CFS and sheathing.

In the past two decades, work that uses finite element modeling packages has been conducted for CFS. The use of these finite element modeling programs allows for further analysis into the behavior of connections that is not always immediately apparent through testing. This is particularly advantageous for connections due to their nonlinear geometric and material behavior during loading.

Chung and Ip (2000), and Salih et. al (2010) created finite element models of CFS connections and compared these results to current design codes to verify the accuracy of the design equations. Salih et. al (2010) used these results to propose new design equations to use in place of those in published design codes. Papers by Chung and Ip (2001), and Kim and Kuwamura (2007) discussed the importance of the calibration of finite element models with actual test data. Chung and Ip’s paper (2001) also focused on calibrating finite element models of high strength, low ductility cold formed steel. Research conducted by Lim and Nethercot (2004) featured both experiments and modeling of cold formed steel moment connections.

A significant aspect of finite element models is the simplification of reality that occurs. This may take place by quantifying failure without the use of damage criteria or crack analysis. Kim and Kuwamura (2007) and Salih et. al (2010) quantified failure within their finite element models in this way. Kim and Kuwamura (2007) discussed three failure criteria: direct stress, equivalent (Von Mises) stress, and equivalent strain. The results of the paper reached the conclusion that the
direct stress criteria provides the most accurate results in their finite element models. Salih et. al (2010) discussed different failure criteria for different failure modes.

The effect of curling on the ultimate strength of connected parts was investigated by multiple researchers (Chung and Ip 2001, Kim and Kuwamura 2007, Salih et. al 2010). Kim and Kuwamura’s paper on modeling stainless cold formed steel (2007) was their first instance discussing the effect of curling, and this effect on the strength of the connection was then quantified through design equations developed in a later paper (2008).

Cold formed stainless steel connections have also been the subject of experiments and finite element models in the literature. Unlike carbon steel, stainless steel has no clear point when transitioning from elastic to plastic under loading, and thus requires different treatment in material modeling. Cold formed stainless steel tests were first began by Johnson and Winter (1966). Kim and Kuwamura (2007) and by Salih et. al (2010) modeled stainless steel connections and compared the model results to experimental results. Salih et. al also compared the results of the model to other design equations, and proposed a new equation based on the findings from the finite element model. Cai and Young (2014) also conducted tests on cold formed stainless steel single shear connections at elevated temperatures.
CHAPTER 2

REVIEW OF THE LITERATURE

Although much work has been done to model bolted connections using finite element analysis programs, the literature lacks work on the modeling of screw fastened connections. The behavior of bolted connections shares many similarities to screw fastened connections, but these two connections have key differences that require specific focus to be made to modeling screw connections.

Unlike bolted connections, screw fastened connections are not accompanied by a nut to secure the connection. This means that screw connections can have the additional failure mode of fastener tilting, which significantly decreases the strength of the connection.

Net section fracture is a common failure mode for bolted connections. Because screws are significantly smaller than bolts relative to the dimensions of their connected parts, net section fracture is not a potential failure mode for screw fastened connections.

Unlike many types of bolts, screws have brittle behavior, which can be seen by the material information available for the two types of fasteners. For bolts, mechanical details like yield stress and tensile strength of the material used to create a bolt are important for design and thus are readily provided by manufacturers. Screws are often case hardened, which changes the behavior of the base metal significantly. This process makes screws very brittle, which is why yield stress and proof stress are often not information available from screw manufacturers.

Due to these differences, the work available in the literature on bolted connections is insufficient in correctly describing the behavior and method of modeling screw fastened connections.
Though finite element modeling of cold formed steel is common, detailed modeling of screw connections is not. This means that tests are often required to determine the stiffness of screw connections so that they may be implemented into larger CFS models. However, requiring tests to calibrate models can become time consuming and expensive. The time needed to complete and validate a finite element model is significantly increased when test data is required. If a finite element model existed that could successfully characterize the stiffness and peak load of screw connections, this model could be modified as needed by any researcher to fit the needs of their larger models.

The purpose of this thesis is to create a robust finite element model of a screw fastened CFS connection. The eventual goal is to use this model to replace the testing that is currently required for screw fastened connections to find its connection behavior. These models aim to capture the stiffness, peak load, and failure mode of any connection, all information that a test would also find. To validate these models, the results of the connections tested by Pham and Moen (2015) will be used. The stiffness information, first peak load, and the failure mode of different tests from their paper are compared to a finite element model to determine the model’s accuracy. The material properties for the CFS of each finite element model will be by Tao and Moen (2017). This is partly because the batch of tensile coupons tested for the Pham and Moen tests had abnormal strengths for some coupons when compared to typical material information for CFS. Tao and Moen’s material information is more representative of typical CFS, and also feature more details (such as strain and percent elongation at failure) that allow for more accurate modeling of the connections. Connections tend to have large amounts of inelastic strain (Salih et.al 2010), so the material properties used require detailed strain information to facilitate accurate results after materials begin to yield.
CHAPTER 3

EXISTING EXPERIMENT INFORMATION

Pham and Moen (2015) conducted a series of tests that had varying ply thicknesses and screw sizes. A portion of these tests were modeled herein. The setup for these tests and the list of models made for this thesis are discussed in the following two sections.

3.1. Test Setup
The setup for the Pham and Moen tests is shown as a schematic in Figure 1. The cold formed steel plies used in the tests were all 152mmx203mm. The overlap area of the two plies was 102mmx102mm, with the screw fastening the plies together located in the center of the overlap. The ply dimensions and the placement of the screw in the connection were designed to ensure that screw tilting, screw shear, and ply bearing failure were the only failure modes that could occur for each connection tested (Pham and Moen 2015). The combination of ply thicknesses tested by Pham and Moen were chosen to cover common CFS framing configurations. Simpson Hex Head X-Screws were used for each test. This screw type is a self-drilling, self-tapping screw, meaning that the screw can be drilled directly into the CFS without a pilot hole required and form its own thread into the holes of both CFS and all tests were identical except for the ply thicknesses used.
Each test was restrained by bolting an aluminum fixture to each ply. The aluminum fixtures restrained out of plane (Z direction) motion for both plies. One fixture, named the “movable fixture” in Figure 1, is where upward displacement (positive Y direction) is applied at a rate of 0.025mm/s. The ply bolted to the movable fixture moves upward in the test, and is always the ply in contact with the screw head. This ply is known as ply 1. The other fixture is fixed to prevent upward motion and is bolted to the other ply. This other ply (that is not in contact with the screw head) is known as ply 2.

The movable fixture continues to apply the displacement load until the screw connection fails. To track the connection behavior until failure, three points are tracked during testing. These points are indicated with the “rods” in Figure 2. On ply 1, the vertical displacement is tracked at a distance 114mm from the bottom of ply 1. On ply 2, the vertical displacement is tracked
25.4mm below the top of ply 2 (Pham and Moen 2015). The difference between the vertical
displacement at the mentioned points on ply 1 and ply 2 is the relative displacement. To track the
failure mode of the connection, the head of the screw is also tracked to determine its angle of
tilting during testing.

Figure 2: Schematic of test measurement setup (Pham and Moen 2015)

3.2. Tests Modeled
The tests by Pham and Moen that are modeled in this thesis use a #10 diameter screw. The tests
modeled are shown in Table 1. Plies 1 and 2 in the tests are the same as in the model. The
“measured thickness” refers to the actual thickness of the plies used in the tests. The naming
notation for the model name refers to the nominal thickness of ply 1 in mils, then the nominal
thickness of ply 2 in mils. For example, the “4368” model has a ply 1 that is 43 mils and a ply 2
that is 68 mils.
Table 1: Model Matrix

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Ply 1 Measured Thickness (mm)</th>
<th>Ply 2 Measured Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3333</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>4343</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td>5454</td>
<td>1.41</td>
<td>1.41</td>
</tr>
<tr>
<td>9797</td>
<td>2.55</td>
<td>2.55</td>
</tr>
<tr>
<td>3368</td>
<td>0.89</td>
<td>1.81</td>
</tr>
<tr>
<td>4354</td>
<td>1.19</td>
<td>1.4</td>
</tr>
<tr>
<td>4368</td>
<td>1.19</td>
<td>1.83</td>
</tr>
<tr>
<td>4397</td>
<td>1.19</td>
<td>2.55</td>
</tr>
<tr>
<td>6843</td>
<td>1.81</td>
<td>1.19</td>
</tr>
<tr>
<td>9733</td>
<td>2.54</td>
<td>0.87</td>
</tr>
</tbody>
</table>
CHAPTER 4

FINITE ELEMENT MODEL

The details of the finite element models made for this thesis is below.

4.1. Finite element analysis product
The product used to build the finite element models used for this thesis was Abaqus CAE version 6.14, using Abaqus/Standard.

4.2. Model Setup
The model setup was designed to closely match the reality of the tests. Many components of the test setup were found to have no effect on the results of the models, so these components were not included in the FE model to reduce the required processing time. The removed components for the screw and the CFS plies are discussed below.

4.2.1. Screw Modeling
Though the screws used in the test have a hexagonal (“hex”) head, a washer, and threads, the screw was modeled as a threadless shank with a circular head and no washer. The inclusion of threads would require manual meshing and complex contact definitions to ensure the connection behavior was correct. Therefore, the screw was modeled as threadless to simplify the model. Because the threads do have an effect on the behavior of the model, their effect on the connection is reflected in the model through the contact definitions discussed in section 4e. The major diameter (including the screw threads) is used for the diameter of the screw in the model. The head of the screw was modeled as a cylinder with the thickness of typical hex heads for #10 screws, and the head diameter listed by Simpson. The washer was not input into the model due to screw connection behavior when in shear. Because the tests are of shear connections, the specific shape and configuration of the head does not have a significant effect on the model. This is
unlike tension connections, where the head type significantly affects the capacity and failure, since pull out and pull over capacities for screws require more interaction with the head and washer throughout the connection. In shear connections, the head and washer of the screw behave as a single unit, and the shank of the screw has the highest effect on the capacity of the connection.

Figure 3: Image of screw used in model (left) vs. Simpson X Screw (ICC 2018) (right) used in tests

4.2.2. Ply Modeling
The length of the plies is the only dimensional difference between the test setup and the model setup for the plies. The length of the plies in the test was 203mm. Because the size of the screw (4.83mm for a #10 screw) is significantly smaller than the size of the plies, the behavior of both plies at a distance far from the screw location has little effect on the connection behavior. Therefore, the ply dimensions used in the model were made to be 152mmx132mm, which significantly reduced the amount of time required to run the models. The full test dimensions (152mmx203mm) were initially input into the model, but a direct comparison of the connection stiffness and peak load when using the smaller ply dimensions currently in the model showed that the shorter plies had no effect on the connection behavior found in the model. The 132mm dimension is used to allow the model to have the same measurement points used in the test to
find relative displacement between the two plies. The measurement points as seen in the model are shown in Figure 4.

![Figure 4: Relative displacement measurement points used in model](image)

The opening for the screw is 102mmx102mm, and the ply dimensions in the model are 152mmx132mm. Except for this opening, the rest of the outer face of each ply is completely restrained from Z direction motion by the fixtures. The fixtures were replaced by boundary conditions in the model at the locations shown in Figure 5.
Figure 5: Typical image of models and locations of aluminum fixture boundary conditions on model

4.3. Screw Material Properties
The material properties used in the model for the screw were based on the information available for Simpson X-Screws from the ICC Evaluation Service (2018). Though Simpson X-Screws are made using Grade 1018-1024 steel, the material properties of this steel type are not appropriate to use for the screw model. Grade 1018-1024 steel is a group of low carbon steels with mechanical behavior that differs from the final screw behavior. Simpson X-Screws, and other screws used in CFS framing, are self-drilling tapping screws. For this screw type to be strong enough to successfully drill through cold-formed steel and form its own thread in the hole, screws are case hardened. Case hardening significantly increases the strength of the screw, but also makes it screw brittle.
The brittle nature of self-drilling self-tapping screws means that the yield strength of the screw used in the tests is not provided by manufacturers. Therefore, the shear strength of the screw was the focus of the material model used in Abaqus, since this is provided by manufacturers. The yield strength needed to successfully model the material in Abaqus can be estimated from the screw’s shear strength, using equation J4-4 from the American Institute of Steel Construction specifications (2016):

\[ F_y = \frac{P_{ns}}{0.6 * A_b} \]  

where \( P_{ns} \) is the shear strength of the screw in Newtons (N) or pound-force (lbf), \( A_b \) is the cross-sectional area of the screw including the threads, and \( F_y \) is the yield strength of the screw. Per the ICC Evaluation Service’s report on Simpson X-Screws (2018), a #10 Simpson Hex Head X-Screw has a shear strength of 7.23kN (1625 lbf) and a diameter of 4.83mm (0.19 in.). Using equation 1, the yield strength of the screw is then approximately 659 MPa (95.64 ksi). In Abaqus, the screw is modeled as elastic-perfectly-plastic. Brittle materials have a tensile strength that is close in value to its yield strength. Therefore, instead of attempting to estimate an ultimate tensile strength value, the screws are assumed to have failed once yield has been achieved through the entire thickness of the screw, since yield strength and tensile strength should be close in value.

The Young’s Modulus of the screw was assumed as 200GPa. This value is typical for Grade 1018-1024 steel. Since the Young’s Modulus is an intrinsic property of a material, the screw should still have the same Young’s Modulus of its base material after case hardening.
4.4. Ply Material Properties

The material properties of the plies were based on tensile coupons from Tao and Moen (2017) and are shown in Table 2. Though ultimate tensile strength and yield strength for the CFS used in the Pham and Moen tests was available, the strain information was not. Because finite element models of connections will achieve highly inelastic strains (Salih et. al 2010), detailed stress-strain properties beyond the ultimate tensile strength values are required to successfully model the behavior of the plies. Abaqus uses true stress and strain for its material properties, so true stress and strains are calculated using equations 2-4, where \( \sigma \) and \( \varepsilon \) are the engineering stress and strain, respectively, and \( \sigma_{true} \) and \( \varepsilon_{true} \) are true stress and strain. If the material properties were based on Pham and Moen, it would not be possible to use true stress and strain due to the lack of strain information available.

Table 2: Ply Material Properties (Tao and Moen 2017)

<table>
<thead>
<tr>
<th>Ply</th>
<th>( t ) (mm)</th>
<th>( F_y ) (MPa)</th>
<th>( F_u ) (MPa)</th>
<th>% elongation at fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>0.90</td>
<td>325</td>
<td>376</td>
<td>0.03</td>
</tr>
<tr>
<td>43</td>
<td>1.12</td>
<td>306</td>
<td>377</td>
<td>0.01</td>
</tr>
<tr>
<td>54</td>
<td>1.43</td>
<td>393</td>
<td>493</td>
<td>0.00</td>
</tr>
<tr>
<td>68</td>
<td>1.80</td>
<td>390</td>
<td>510</td>
<td>0.03</td>
</tr>
<tr>
<td>97</td>
<td>2.56</td>
<td>379</td>
<td>505</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\[
\varepsilon_{true} = \ln(1 + \varepsilon) \tag{2}
\]

\[
\sigma_{true} = \sigma(1 + \varepsilon) \tag{3}
\]

Beyond the ultimate tensile strength value, equation 3 no longer applies due to necking. The engineering stress-strain curve will show the fracture stress to be lower than the ultimate tensile strength, but the necking effect will cause the true fracture stress to rise above the true ultimate
tensile strength due to the severe reduction in cross sectional area. When necking occurs, one method to determine the true stress and strains beyond the ultimate tensile strength is to measure the instantaneous cross-sectional area of the coupon during testing. The cross-sectional area of the tensile coupons was not measured instantaneously in Tao and Moen’s tensile coupon tests, but based on tabulated fracture strains in Salih et. al (2010), the strain at fracture can be assumed to be approximately 100% for steel. Therefore, the true stress-strain curve will be extrapolated to a strain of 100% for the material data of all plies modeled. The true stress past the ultimate tensile strength until 100% strain can then be determined using equation 4 (Dowling 2013):

\[ \sigma_{true} = K \epsilon_p^n \]  \hspace{1cm} (4)

where \( K \) is the strength constant, \( n \) is the strain hardening exponent, and \( \epsilon_p \) is the plastic strain. \( K \) and \( n \) can be found by substituting values for true stress and strain found using equations 2 and 3 into equation 4. This eventually leads to the final true strain at fracture being equal to the \( K \).

The Young’s Modulus for the plies in all models was approximately 204GPa, typical for CFS. The slope of the stress-strain curves from Tao and Moen all showed a Young’s Modulus of this value prior to yield.

4.5. Boundary conditions
The boundary conditions of all models were based on the test setup. The location of boundary conditions on the plies in the model is shaded in red in the below figures. The bottom of Ply 2 was fixed at the bottom from movement in the Y (vertical) direction to represent the bolt connecting Ply 2 to its aluminum fixture in the test.
The sides of both plies were fixed from lateral and out of plane motion (X and Z) to represent a “web stiffened by flanges” as discussed by Pham and Moen (2015) and can be seen in Figure 7.
The last boundary condition in the model is to restrain out of plane motion of the faces of the plies in the Z direction. The aluminum fixtures bolted to the plies prevented any curling or other out of plane motion that can occur during loading. Boundary conditions restraining lateral and out of plane motion outside of the 102mmx102mm screw opening prevented Z direction motion without the need to include the fixtures in the model. The location of these boundary conditions can be seen by the shaded areas on the plies in Figure 8.

Figure 7: Boundary condition on edges of both plies (front view of model)
Figure 8: Boundary conditions restraining out of plane motion. Left: Front of model. Right: Back of model.

The load was applied in the test using displacement control to the top of Ply 1. The test was conducted by applying displacement at a rate of 0.025mm/s, and this speed of load application was also used in the model. This monotonic loading protocol can be seen in Figure 9.
4.6. Contact Definitions
The contact definitions for all models had the same key components. Tangential and normal contact behavior were defined for all surfaces in contact. Tangential contact behavior was the same for all surfaces in contact in all models, and the normal contact behavior varied in each model. Both are described in further detail below.

4.6.1. Tangential Contact Definitions
Tangential behavior was used to define the sliding contact behavior between any surfaces in contact in the model. Isotropic coulomb friction with penalty behavior was the friction method used for all surfaces in contact. The friction coefficient used was 0.2, based on parametric studies conducted on the effect of this friction coefficient in Abaqus by Chung and Ip (2000). All other tangential behavior was left as default in Abaqus.
4.6.2. Normal Contact Definitions
Normal contact behavior was specified for all contact surfaces. The contact pressure-overclosure relationship is a key factor in defining the normal contact behavior. In Abaqus, normal contact is defined by specifying the amount that one surface (the “slave” surface) can penetrate another surface (the “master” surface). The relationship chosen was a “hard” contact relationship, which aims to make the amount of penetration that can occur between the slave and master surfaces as small as possible (Abaqus Analysis User’s Guide 2014).

The default hard contact relationship is insufficient to successfully model the behavior of screw connections. This is because the default relationship does not allow for enough surface penetration to occur. Screw connections have coarse threads, or a small number of threads relative to the length of the fastener. For example, the screw used in the tests is a 10-16, so only 16 threads per inch are on the length of the screw shank. This means that despite the threads playing a key role in the connection behavior of screw fastened connections, only about one or two threads on the screw will be engaged with the CFS plies at the beginning of any test. The small amount of threads per inch on the shank of the screw means that the threadless portions of the screw shank will likely come in contact with the plies during loading. Since the threadless shank of the screw has a smaller diameter than the threaded and nominal diameter of #10 screws (the same diameter used in the screw model), the contact relationship between the screw and the plies must allow for some penetration of the plies into the screw to accurately reflect the plies interacting with the threadless shank of the screw during loading. The amount of penetration required to accurately represent this contact behavior is significantly higher than the default penetration allowed with hard contact. In the models, the amount of penetration allowed between the screw shank and a ply had a strong effect on the stiffness of the connection. The lower the
amount of penetration allowed between the shank and the ply, the higher the connection stiffness of the model.

To understand the method used in the model to reduce the stiffness of the connection behavior (and increase the amount of surface penetration between the shank and the ply), the way that Abaqus defines contact requires further discussion. In Abaqus, contact occurring is defined by contact pressure. If a surface is not in contact with another surface, the contact pressure is zero. Abaqus will register contact when the contact pressure becomes greater than zero. The contact pressure during contact increases as the amount the slave surface penetrates the master surface increases. The value of contact pressure divided by penetration is known as the contact stiffness, and will be referred to as $K$. For a default hard contact relationship, the $K$ is essentially infinity, allowing for almost no penetration between two surfaces in contact. (Abaqus Analysis User’s Guide 2014).

To reduce the stiffness of the connection behavior, the constraint enforcement method, which controls the behavior of the hard contact, is changed from default to penalty. With the penalty method, the hard contact relationship can be softened to allow for more penetration through the control of the contact stiffness $K$. The default $K$ is based on the Young’s Modulus values provided for the model components, and thus $K$ can be large. The nonlinear penalty option allows for various parameters to control $K$, with their uses explained in Figure 10 and below.
The first parameter is the maximum, or final contact stiffness $K_f$. The maximum contact stiffness occurs once a certain amount of penetration $d$ has occurred between the slave and master surfaces. At this point, the contact pressure begins to rapidly increase at rate $K_f$ with any further penetration.

Figure 10: Nonlinear penalty contact behavior in Abaqus (Abaqus User’s Guide 2014)
The initial stiffness $K_i$ is typically low relative to the maximum stiffness and allows a larger amount of penetration to occur at the beginning of contact occurring between two surfaces. The beginning of the contact is when the contact pressure becomes greater than zero, which occurs once there is no clearance between the two surfaces. The value that defines the clearance is $C_0$, which is set to zero for all models and can be seen on the horizontal axes of the Figure 10 curves. $K$ begins to increase from $K_i$ at penetration value $e$ (the lower quadratic limit) to $K_f$ once penetration $d$ (the upper quadratic limit) is reached. Parameters $e$ and $d$ are controlled by the user by scaling the characteristic lengths between two contact surfaces. The characteristic length for each pair of contact surfaces is set by Abaqus.

The values for the contact parameters chosen in each model produce the best combination of failure mode, connection stiffness, and peak load accuracy of the model compared to Pham and Moen’s tests. The penalty parameters chosen for each model are below in Table 3 and were found based on a parametric study of each variable as discussed in section 5.2. Models in the table that have two values for a single parameter (such as 3500/1312.5) indicate that the ply 1-to-screw parameter is a different value than the ply 2-to-screw parameter. Ply 1-to-screw parameter values are first, followed by the ply 2-to-screw value.
Table 3: Nonlinear penalty parameters used for each model

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Maximum Stiffness (N/mm)</th>
<th>Initial Stiffness (N/mm)</th>
<th>$e/d$ (in./in.)</th>
<th>Characteristic Facet Length Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>3333</td>
<td>50000</td>
<td>2000</td>
<td>0.9999</td>
<td>0.625</td>
</tr>
<tr>
<td>4343</td>
<td>500000</td>
<td>3500</td>
<td>0.9999</td>
<td>0.300</td>
</tr>
<tr>
<td>5454</td>
<td>280000</td>
<td>2625</td>
<td>0.9999</td>
<td>0.750</td>
</tr>
<tr>
<td>9797</td>
<td>2000</td>
<td>1800</td>
<td>0.9999</td>
<td>1.000</td>
</tr>
<tr>
<td>3368</td>
<td>50000</td>
<td>1500/45000</td>
<td>0.9999</td>
<td>1.000/0.300</td>
</tr>
<tr>
<td>4354</td>
<td>500000/140000</td>
<td>3500/1312.5</td>
<td>0.9999</td>
<td>0.300</td>
</tr>
<tr>
<td>4368</td>
<td>500000</td>
<td>2500</td>
<td>0.9999</td>
<td>0.300</td>
</tr>
<tr>
<td>6843</td>
<td>500000</td>
<td>2500</td>
<td>0.9999</td>
<td>0.300</td>
</tr>
<tr>
<td>9733</td>
<td>50000</td>
<td>1100</td>
<td>0.9999</td>
<td>0.600</td>
</tr>
</tbody>
</table>

4.7. Mesh details
Solid elements were used for both the CFS plies and the screw. CFS has very high length and width to thickness ratios, which normally makes shell elements more appropriate to model the material. However, the behavior at the hole between the screw and the CFS is the focus of the model. If the CFS plies were shell elements, the hole would be represented by an edge, meaning that contact between the screw and the plies would have not been possible to define.

Fully integrated C3D8 elements were used for the CFS and the screw. This element type was found to consistently produce the best combination of failure mode, peak load, and stiffness for all models when compared to reduced integration elements or incompatible mode elements.

All models had 8 elements in the thickness of the CFS plies. This number of elements allowed enough degrees of freedom to be within the solid elements to ensure accurate results. The focus
of the connection behavior is at the hole so the mesh was made finer at that point. At the hole, the mesh size was the thickness of the CFS plies x one eighth of the ply thickness. The mesh size 12.7mm from the center of the hole was 10x larger than the ply thickness x one eighth of the ply thickness. Having a coarser mesh far from the hole was shown to have little effect on the results of the model, but significantly reduced the run time for each model.

Figure 11: a) Overall ply mesh b) Elements in thickness on edge of ply c) Detail of mesh at hole

The mesh size for the screw was defined to be half the thickness of the thinnest ply in each model. Abaqus recommends that the surface with a coarser mesh should be the master surface (Abaqus Analysis User’s Guide 2014), so this mesh size made it appropriate for the screw shank to be the master surface and allowed for accurate results.
4.8. Failure Criteria
In Pham and Moen’s tests, the cause of failure can be found through a visual inspection of the behavior of the plies and screw during loading. For example, connection failure due to tearing of the ply or a screw breaking from shear can be clearly seen in a test. In the models, the only way that such behavior can occur is if the material model of the plies and screw incorporated damage criteria. Damage criteria was not included in the material of the ply or screw. This is because the material information available for the screw or by Tao and Moen (2017) for the plies does not include information that could be used to build the damage criteria. Therefore, model failure must be determined without damage. The failure criteria discussed in sections 4.7.1-4.7.4 are used instead to provide a consistent method of determining the failure behavior of all models.

4.8.1. Failure Modes
There are five critical failure modes in typical screw fastened connections. These are screw tilting, ply bearing, a combination of tilting and bearing, screw shear, and ply bearing with screw shear. Tilting failure occurs when the screw angle increases to the point that the connected parts begin to separate, and the screw pulls out of one of the plies. Bearing failure occurs after the hole of one of the plies is stressed beyond yield due to the force of the screw on the hole. This causes
the hole to elongate and makes the connection ineffective. A combination of tilting and bearing occurs when the screw angle causes the connected parts to separate, and hole elongation occurs at the same time. Screw shear is when the screw breaks in two due to the applied load on the connection. These failure modes are all captured in the tests and the models.

4.8.2. Screw Shear and Screw Tilting Failure Criteria
As the model does not capture fracture in fasteners, it is necessary to develop a failure criterion to determine whether shear failure has occurred. Screw shear is defined as the point when elements through the entire thickness of the screw have reached yield. Because screws are brittle, a screw that has exceeded yield through the thickness will fail soon after due to the low strain allowed in a brittle material prior to fracture. In the models, screws that reach yield through the thickness were typically accompanied by a notable decrease in their cross-sectional area at the point in the screw where shear failure would occur. This further validates this failure criteria, and this screw behavior is shown in Figure 13. Because the model does not have damage criteria, a decreasing cross section such as in Figure 13 is sufficient in visually indicating that screw shear is occurring in the model.

Figure 13: Model failing by screw shear
Yield is determined based on the Von Mises yield criterion. The yield stress for all screws modeled is 659 MPa. If a continuous line of elements can be formed that have an equivalent Von Mises stress of 659 at all their integration points, yield has been reached in the thickness of the screw, and thus screw shear failure has occurred. This is shown in Figure 14.

Figure 14: Undeformed view of screw in model failing by screw shear, shown by line of yielded elements

Screw tilting in the model is determined by examining the screw head. The angle of the screw head after loading is determined by finding the amount of displacement that has occurred at the center of the head in the Y and Z direction at peak load. Screw tilting is considered to be the cause of failure if the tilting angle exceeds 10 degrees at peak load per Corner (2014), and if screw shear is not also occurring. Because damage is not incorporated into the model, a screw that is shearing off in the model may have its head continue to tilt, since the screw will never break in two in the model.

4.8.3. Ply Failure Criteria
The other tilting criterion for tilting failure is based on the plies. Unlike other criteria, this is solely based on a visual examination of the model. Eventual tilting failure occurs when the screw pulls out of one of the plies. For this to happen, the plies must separate, so a notable separation of ply 1 and ply 2 at the hole at peak load should also be present in any model that fails by tilting.
To determine if a ply has yielded, the elements in the bottom half of the hole of Ply 1 and the top half of the hole of Ply 2 are checked. Using the Von Mises yield criterion, a ply element is considered to have yielded if all integration points on the element have an equivalent Von Mises stress that exceeds the yield stress.

For bearing failure, two checks are done to confirm bearing failure is occurring. The first is to determine if the elements mentioned in the previous paragraph have yielded for either ply at peak load. The second is based on work by Yu and Xu (2010) on CFS bolted connections. In their paper, they determined that bearing failure can be considered to occur after a 12.8mm hole has been stretched an additional 6.4mm vertically, which is 50% elongation of the hole. The same concept is applied to determine bearing failure in the models. A 4.83mm diameter screw is used, so bearing failure is considered to occur when the hole has stretched an additional 2.42mm vertically, or 50% elongation at peak load. This elongation must occur at both edges of the hole in a ply to be considered bearing failure. Because bearing failure deformation limits are somewhat arbitrary, and are not specified for screws in AISI, an arbitrary limit similar to bolted connections is adopted in this thesis solely to act as a way to differentiate between other failure modes.

4.8.4. Combination Failure Criteria
Connection failure may occur due to two failure modes happening at the same time, or a different failure mode occurring at the final displacement of the test compared to at peak load. In the series of tests conducted, tilting and bearing failure was a common combination. In the model, at least one of the criteria must be met for both failure modes in a combination. For example, if at peak load, the hole has reached 2.42mm elongation and the screw head has tilted more than 10 degrees, the failure mode is a combination of tilting and bearing. One failure mode
dominates if all its failure criteria have been met at peak load. For example, if all the tilting failure criteria have been met at peak load (but not all bearing failure criteria) but the model aborts at a point where one or both bearing failure criteria have now been met, the failure mode is considered “tilting-dominated tilting and bearing”.

Ply configurations where one ply is over twice the thickness of the other ply can have bearing failure at peak load due to the thin ply, and then have screw shear at the final displacement due to the thick ply. This failure mode is considered “bearing-dominated failure with screw shear”.

Models that fail by screw shear cannot have a combined failure mode with screw tilting. As seen by Figure 13 and Figure 26 for example, there is notable tilting that can be seen in the screw head despite the visible deformation in the screw shank. However, this screw tilting is only due to the lack of damage criteria incorporated into the model. Because the screw cannot break in two due to shear in the model, this results in the screw head being able to tilt after screw shear failure criteria has been met.
CHAPTER 5
RESULTS AND DISCUSSION

5.1. Results
The results of the Abaqus models are below. The mode of failure for each model will be discussed, followed by results of the peak load and connection stiffness for each model.

5.1.1. Failure Mode
The failure mode results of the models with a comparison to Pham and Moen’s corresponding tests are all discussed below.

5.1.1.1. Screw Tilting and Bearing: Same Ply 1 and 2 Thickness
The 3333 tests failed due to tilting and bearing, with failure dominated by tilting. The average tilting angle for this set of tests was recorded as 19.5 degrees. In the model, the tilting angle at peak load was recorded as 22 degrees. Visible ply separation at the bottom of the hole for this model can also be seen in Figure 15c. Since the tests and model both exceed 10 degrees of screw tilting and the model has ply separation, the model and the test both meet the tilting failure mode criteria.

The model met one of the two bearing failure criteria at peak load. The elements of interest in Ply 1 and 2 at the hole had all exceeded yield at peak load. The model did not meet the bearing elongation criteria at peak load or at its final displacement, with the maximum elongation of the hole being less than 50% of the hole diameter at peak load and at model failure.

As shown in Figure 15a and b, bearing occurs in both plies in the model. Like the tests shown in Figure 16, the model has the most severe bearing on ply 1 at the bottom of the hole, and slight bearing occurs at the top of ply 2. The ovalization of the ply 2 hole shown in Figure 16c does not
occur in the model. As seen in Figure 15b, the bottom of the ply 2 hole is no longer in contact with the screw at peak load, which makes that deformation of ply 2 not possible in the model.

Figure 15: 3333 model a) Ovalization of ply 1 hole b) Minor ovalization of ply 2 hole c) Screw tilting and ply separation
The 4343 tests failed in the same way as the 3333 tests, by tilting and bearing, with tilting dominating the failure. The average tilting angle at peak load for the 4343 tests is 18.8 degrees. In the model, the tilting angle at peak load was 23 degrees. Because the tests and the model both have a tilting angle that exceeds 10 degrees (Corner 2014), tilting failure is considered one of the causes of failure.

The elongation bearing criteria were also not met in the 4343 model, though the elements of interest in both plies had all exceeded yield. Figure 17 shows the bearing that occurs on both plies of the model. The ovalization effect seen in Ply 2 (Figure 18c) is less severe in this test than in the 3333 test, and does slightly occur in the model, as seen by Figure 17.
Figure 17: 4343 model a) Ply 1 bearing b) Ply 2 slight hole bearing c) Screw tilting and ply separation

Figure 18: Photo of 4343 test from Corner (2014) a) Screw head tilting in ply 1 b) screw shank in ply 1 c) ovalization and bearing of ply 2 hole
5.1.1.2. Screw Tilting and Bearing: Different Ply 1 and Ply 2 Thickness

These models that failed by tilting and bearing had different behavior than the same ply thickness group. This group contains models 3368, 4354, and 4368. In this group, all criteria for bearing failure is met at peak load or soon after peak load is reached.

For the 3368 tests, failure was due to tearing of ply 1, which occurs due to bearing failure of ply 1. Tilting occurs on ply 2, though this does not control the failure. The tilting angle at peak load was 34 degrees. For bearing, only the yield criteria for bearing had been fully met at peak load for ply 1. Figure 19 shows the behavior of the 3368 model at peak load. Though the tilting angle is high for this model, the thickness of ply 2 causes there to be little ply separation. Unlike the 4343 or 3333 models, where ply separation at the bottom of the hole occurs with a higher screw tilting angle, the screw in the 3368 model directly bears on ply 1 as the tilting angle increases. The failure mode of the model is considered tilting and bearing. This is because at peak load, only one of the two criteria were met for both tilting and bearing, so neither could dominate at peak load. After peak load however, bearing dominated the response. In Figure 36, the force-displacement curve for the 3368 model can be seen to remain constant after peak load. This means that enough bearing stress was been applied to ply 1 in the model to cause the hole to continue to elongate at a constant bearing stress and exceed the 50% elongation criteria after peak load is reached.

The 3368 test behavior is shown in Figure 20. Though bearing failure clearly occurs in ply 1 of the tests, the ply tearing is not possible in the current model. No damage criteria has been input into the model, so degradation of the material can not be fully replicated in the model.
Figure 19: 3368 model at peak load with a) Ply 1 (33 mils) under bearing b) Ply 2 (68 mils) with bearing at top of hole c) Overall connection

Figure 20: 3368 test (Corner 2014) a) Ply 1 hole tearing b) Screw head in ply 2 after ply 1 tearing c) screw shank in ply 2
The 4354 and 4368 tests had similar behavior. Both had significant fastener tilting, eventually leading to the screw pulling out of the connection, causing failure. This can be seen in Figure 21 below.

![Image](image_url)

Figure 21: 4354 test (Corner 2014) a) Ply 1 bearing and head tilting b) Screw shank in ply 1 c) Ply 2 hole bearing

At peak load, the 4354 model had a screw tilting angle of 28 degrees and the 4368 model had an angle of 30 degrees. At this point in both models, visible bearing can be seen at the hole of both plies, and 25% hole elongation has occurred on ply 1. Both plies in both models have exceeded yield at the relevant elements on the hole, and thus have met the yield criteria for bearing failure. Though the amount of tilting shown in Figure 21 does not occur in the models at failure, the ply separation shown in Figure 22c and Figure 23c at peak load indicates that tilting-dominated tilting and bearing is the failure mode for these models. Also, by comparing Figure 22 and Figure 23, though the peak load for these two models are different, it should be noted that the deformation of the plies and screw in both models is identical due to only a slight increase in the thickness of ply 2.
Figure 22: 4354 model a) Ply 1 bearing and ovalization b) Ply 2 deformation at top of hole c) Fastener tilting and ply separation
5.1.1.3. Screw Shear: Same Ply 1 and Ply 2 Thickness
The 5454 and 9797 tests are in this group. These tests failed entirely due to shear, with minimal screw tilting or bearing on the plies.

The 5454 test has an average screw tilting angle of 13 degrees at peak load. Though this normally would be considered a tilting failure mode, per Corner (2014) and Figure 24, the 5454 tests had tilting occur only in the screw head, while the screw shank still had a low tilting angle. Because of this consistent issue in these tests, screw shear is still considered the mode of failure for this test and not tilting.
The 5454 model had a different failure mode than its corresponding test. The magnitude of peak load and the contact parameters used to achieve correct connection stiffness caused tilting to occur instead of shear at peak load. However, it should be noted that the model is close to achieving screw shear. In Figure 25, the elements in the screw at failure that have a Von Mises stress exceeding 630 MPa are indicated with the continuous red line on the screw. Since the yield stress of the screw was selected to be 659 MPa, a slightly higher peak load would have resulted in screw shear.
The 9797 test had very small tilting of the screw before screw shear, with a recorded tilting angle of 1.5 degrees (Corner 2014). In the model, the screw tilting angle was neglected because of the difference in the model and test behavior. The screw will never fully break without incorporating damage criteria into the model, so the angle of the head may increase, but has no real effect on the failure mode or the model behavior. Also, as seen in Figure 26, there is no ply separation occurring in the model, so any tilting is not resulting in a tilting failure mode as it does for other models.

![Figure 26: 9797 model failing in shear](image)

The primary difference between the 9797 tests and model is the degree of bending that occurs in the screw. Figure 27 shows that the screw shank remains horizontal in the tests, while the screw shank in the model has significant bending. Again, this is because the screw cannot break in two
in the model as it does in the tests. As the displacement applied in the model increases, the screw shank continues to bend downward to maintain equilibrium in the screw.

Figure 27: 9797 test (Corner 2014) a) Screw head after failure b) Sheared off screw in ply 1 c) Screw shank in ply 2 after failure

5.1.1.4. Screw Shear: Different Ply 1 and Ply 2 Thickness
The 4397, 6843, and 9733 tests are in this group. All these tests failed by screw shear, but the 4397 and 9733 also had bearing failure in the thinner ply, resulting in the thinner ply tearing. The 6843 tests failed by screw shear prior to any significant bearing occurring.
The 4397 and 9733 test failure are similar, with the failure of 9733 shown in Figure 28 below.

Figure 28: 9733 test (Corner 2014), with similar results in 4397 test a) Sheared off screw b) Ply 2 ovalization c) Folding of ply 2 and bearing

The 9733 model initially had significant bearing failure in ply 2, which was followed by screw shear. The screw shear in this model is not visible, but the line where yield in the thickness occurs is indicated in red in Figure 29a. The contact parameters were calibrated in this model by prioritizing connection stiffness over the failure mode. This resulted in the screw shear here being less visible than in other models, while allowing this model to still have good agreement with the connection stiffness of the tests. This issue with the contact parameters is the same issue that caused the 5454 model to fail in tilting rather than shear.
The 4397 model, shown in Figure 30, had similar behavior to the 9733 model. Ply 1, which is the thinner ply, had significant bearing failure at peak load. Unlike 9733, the 4397 model already had visible screw shear occurring at peak load. Both the 9733 and 4397 models have bearing-dominated failure with screw shear, because all bearing criteria are met at peak load, with screw shear occurring either soon after peak load or at the final displacement.
The 6843 model, shown in Figure 31, has visible screw shear occurring at peak load. Also, the bearing in the 43 mil ply of the model has caused the hole to have yielded and elongated slightly past the 50% minimum for bearing at peak load. Because screw shear and bearing failure occur at peak load, the failure mode for this model is bearing-dominated failure with screw shear. The failure of the 6843 test is shown in Figure 32, showing that bearing also occurred on ply 2 in the tests.
Figure 31: 6843 model at peak load a) Ply 1 b) Ply 2 bearing failure at top of hole c) Screw shear and ply 2 bearing

Figure 32: 6843 test (Corner 2014) a) Sheared off screw in ply 1 b) Screw shank in ply 2 after failure c) Screw after failure in ply 2
5.1.2. Peak Load and Stiffness in Tests vs Model
A comparison of the peak load and the stiffness prior to peak load for all models and their corresponding tests is in this section.

The peak load will be defined as the maximum load in the model at the first peak. Because the models consistently captured post-peak degradation behavior, the peak load for each model is confirmed to be accurate. The stiffness characterization used in the model is the same method adopted by Pham and Moen (2015) shown in Figure 33. The stiffness of the model will be characterized linearly by selecting points at 40% (P₁), 80% (P₂), and at 100% (P₃) of peak load.

![Stiffness Characterization](image)

Figure 33: Pham and Moen stiffness characterization (2015)

5.1.2.1. Screw Tilting and Bearing: Same Ply 1 and Ply 2 Thickness
The peak load found for the 3333 model was 2.95kN. The average peak load in the tests was 3.07kN per Pham and Moen (2015). The peak load found using the model is therefore only 3.9% lower than the test peak load. Table 4 compares the stiffness from each 3333 test to the model.

50
As seen in Table 4, the model has mostly good agreement with the stiffness at 40% peak load, except for Test 2, which has a 40% stiffness 33% higher than the model.

The stiffness at 80 and 100% of peak load are consistently higher in the model than the tests based on Figure 34. This is due to the difference in the behavior of the model and the tests. The force-displacement curve at 80% load for each test is where a noticeable softening of the curve occurs. Once the softening occurs in the tests, the peak load occurs at a relative displacement
much larger than the displacement at 80% peak load. In the models, this softening occurs, but peak load occurs soon after. This causes the stiffness of the model to be higher than the tests for 80% and 100% of peak load. This same issue is present in all models where tilting dominates in failure.

The peak load found for the 4343 model was 4.36kN. The average peak load in the tests was 4.87kN per Pham and Moen (2015). The peak load from the model is thus 10.5% lower than the tests.

Figure 35: 4343 Model vs Test Results
The 40% of peak load stiffness of the model shows good agreement with the tests at 40% peak load. The max percent difference between the model and test 40% stiffness is 16.7%. Considering that the 40% stiffness of the tests vary up to 25% between the three tests, this is acceptable. As discussed in the 3333 stiffness comparison, the 80% and 100% stiffness from the tests are always lower than the model stiffness. Both 4343 and 3333 had tilting dominated failure, and these curves both have the same post peak behavior, indicating that this is not an error in the force-displacement curves from the model.

### 5.1.2.2. Screw Tilting and Bearing: Different Ply 1 and Ply 2 Thickness

The 3368, 4354, and 4368 tests failed by tilting and bearing. This group of models have more severe bearing failure than the “same ply thickness group” discussed in the previous section, as well as other differences that require discussion in this section. The connection behavior of these models is discussed below.

The 3368 model had a peak load of 4.06kN, while the average peak load from the tests is 5.53kN. This test peak load is from Corner (2014) for the 3368 tests, as the peak loads listed by Pham and Moen (2015) for this test neglect the first peak of one of the tests. The peak load from the tests is 26% higher than the model. Though this normally indicates very poor agreement, there is significant variation in the peak load of each test that skews these results. The standard deviation of the test peak load from the mean is 1.54kN. At 4.06kN, the peak load of the model is still within the standard deviation of the test results and will therefore be considered
acceptable. No other ply configurations have such a high variation in peak load of the tests, so this check of the standard deviation is not necessary when analyzing any other models.

Table 6: Model and test stiffness comparison for 3368 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>5.21</td>
<td>4.90</td>
<td>5.21</td>
<td>3.84</td>
</tr>
<tr>
<td>80</td>
<td>3.14</td>
<td>1.61</td>
<td>1.18</td>
<td>0.43</td>
</tr>
<tr>
<td>100</td>
<td>0.44</td>
<td>0.29</td>
<td>0.63</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Figure 36: 3368 model vs test results

The model stiffness shows good agreement with the test stiffness. 80% stiffness is higher in the model than the tests, but the 40% and 100% peak load stiffnesses are close in value to the tests.
The failure mode section discussed the tearing of the ply 1 hole that occurred in this test. That is a severe bearing failure and is shown by the force-displacement curve behavior of the model in Figure 36. After peak load is reached, the force remains constant until the model aborts, which indicates that bearing dominated the post peak load response of the model. At peak load however, tilting and bearing is the failure mode of the model since only one of the two criteria for both tilting and bearing are met.

The 4354 tests had an average peak load of 5.54kN. The 4354 model had a peak load of 4.65kN. The model has a 16% lower peak load than the tests. Figure 37 shows that unlike the 3368 tests, the peak load of the 4354 tests has very little variation, so the peak load of the 4354 model has poor agreement with the tests.
The behavior of the force-displacement curve is similar to the 3333 and 4343 models. After peak load, the force sharply decreases until the final displacement. This post peak behavior has been shown to indicate fastener tilting controlling failure for the 3333 and 4343 models, and holds true for the 4354 test, which also fails by fastener tilting.

The 4354 stiffness values show acceptable agreement with the test results. 80% and 100% model stiffness are both too high, but that effect is mitigated by the 40% stiffness being very close to the test results.
Table 7: Model and stiffness comparison for 4354 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>7.21</td>
<td>5.78</td>
<td>9.92</td>
<td>9.16</td>
</tr>
<tr>
<td>80</td>
<td>4.17</td>
<td>2.78</td>
<td>3.01</td>
<td>2.45</td>
</tr>
<tr>
<td>100</td>
<td>0.82</td>
<td>0.66</td>
<td>0.55</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The 4368 tests had an average peak load of 6.28kN. The model had a peak load of 4.69kN, 33% lower than the tests. Like the 4354 tests, there was little variation in the peak load of the tests, so the model has very poor agreement with the peak load of the tests. The comparison of the force-displacement curves of the tests and model is shown in Figure 38.

Table 8: Model and test stiffness comparison for 4368 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>6.92</td>
<td>11.85</td>
<td>4.85</td>
<td>9.64</td>
</tr>
<tr>
<td>80</td>
<td>5.59</td>
<td>3.20</td>
<td>3.39</td>
<td>2.81</td>
</tr>
<tr>
<td>100</td>
<td>0.84</td>
<td>0.87</td>
<td>0.81</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Though the stiffness of the 40% and 80% stiffness of the 4368 model do not show good agreement with the test, the 100% stiffness has very good agreement based on Table 8. Also, the behavior of the connection before peak is acceptable when the stiffness of the connection is considered overall. Because the peak load and post-peak force displacement curve behavior of this model is not consistent with the behavior of other models with a similar failure mode, more work must be done to determine the issues with this model. These issues are discussed further in section 5.4.4.
5.1.2.3. Screw Shear: Same Ply 1 and Ply 2 Thickness
As discussed in the failure modes section, tests 5454 and 9797 failed due to screw shear. The behavior and peak load of these models is discussed below.

The peak load found for the 5454 model was 6.09kN and the average first peak load in the tests was 6.16kN per Corner (2014). The peak load found using the model is thus 1.1% lower than the test peak load. Corner’s results for peak load were compared in lieu of Pham and Moen for the 5454 tests due to a discrepancy in the peak used. The peak load in all tests should be based on the first peak of every test per Pham and Moen, but Pham and Moen listed the force from the second peak as the peak load for all the 5454 tests in the paper. Corner’s listed peak loads for the
5454 tests aligns with the first peak, and thus was used instead. Table 9 compares the stiffness from each 5454 test to the model.

Table 9: Model and test stiffness comparison for 5454 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>6.84</td>
<td>9.36</td>
<td>10.03</td>
<td>7.95</td>
</tr>
<tr>
<td>80</td>
<td>4.10</td>
<td>3.91</td>
<td>3.31</td>
<td>3.63</td>
</tr>
<tr>
<td>100</td>
<td>0.93</td>
<td>0.48</td>
<td>0.39</td>
<td>0.41</td>
</tr>
</tbody>
</table>

In Figure 39, the model results vs the test results can be seen. The test results show good agreement with the model results, with the stiffness aligning closely with the test data. As discussed in the failure mode section, the 5454 model fails by tilting. The tilting deformation of
the screw head in the tests is explained by Corner (2014), where only the screw head deformed while the shank had minimal tilting. This caused the first peak of each 5454 test to occur due to tilting. Because the actual failure mode of these tests is shear, the second peak of Tests 2 and 3 is due to screw shear. The initial head tilting controlled the failure for the 5454 model, which is why the model peak load aligns closely with the first peak of the tests (which is due to tilting) and does not reach visible screw shear.

The 40% stiffness of the 5454 model is 25% lower than the average 40% stiffness in the tests, but this is likely due to the discrepancy in the peak load of Pham and Moen compared to Corner. The value for peak load used in Pham and Moen is higher than the first peak, which can result in a higher 40% stiffness than is occurring. As discussed in the tilting and bearing results, the 80% and 100% stiffnesses of the model are higher than the tests since the methods used to change the model stiffness are based on primarily matching the 40% stiffness of the connection.

The average peak load for the 9797 tests was 6.6kN per Pham and Moen (2015). In the model the peak load was 6.98kN, 5.7% higher than the tests. This shows that the 9797 tests had very good agreement with the peak load results from the model. However, the 40%, 80%, and 100% stiffness of this model were very inaccurate. The methods used in all other models fix this stiffness were unsuccessful, so the discussion of this model’s behavior will be in the Future Work section 5.4.4.

5.1.2.4. Screw Shear: Different Ply 1 and Ply 2 Thickness
Tests in this section failed due to screw shear, but also had significant bearing failure in the thinner ply. The tests in this section are 4397, 6843, and 9733. The behavior of these tests when compared to their models is discussed below.
For test 4397, the average peak load was 7.62kN per Corner (2014). Like the 5454 tests, Pham and Moen based the peak load on the peak associated with screw shear instead of the actual first peak of the model, so Corner’s listed peak loads for the same tests are used instead. In the model, the peak load was 7.35kN, 3.5% lower than the tests. The stiffness comparison is in Table 10.

Table 10: Model and test stiffness comparison for 4397 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>7.9</td>
<td>8.61</td>
<td>10.71</td>
<td>8.52</td>
</tr>
<tr>
<td>80</td>
<td>2.37</td>
<td>2.95</td>
<td>4.33</td>
<td>1.47</td>
</tr>
<tr>
<td>100</td>
<td>0.47</td>
<td>0.51</td>
<td>0.60</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Figure 40: 4397 model results vs test results
The 4397 model stiffness shows a good agreement with the stiffnesses characterized by Pham and Moen (only 3 of the 5 tests were characterized). The connection stiffness and peak load are directly connected in the model, so increasing the 40% stiffness would cause a higher than desired peak load. Because of this, the 40% stiffness was set to be slightly lower than the tests to allow for a more accurate peak load. Screw shear did occur at the final displacement for the model, but prior to screw shear, the model’s connection behavior is controlled by the bearing on ply 1 (43 mils), which is much thinner than ply 2 (97 mils). Bearing in the stiffness behavior is seen through a constant horizontal force-displacement curve after peak load is reached. In the model, the max decrease in the force after peak is reached is from 7.35kN to 7kN, only a 4.3% decrease. This decrease is small enough to be neglected, so the 4397 force displacement curve can be treated as a constant line after peak load.

The 6843 model had a peak load of 6.87kN. The average peak load of the 6843 tests is 6.45kN per Pham and Moen (2015), so the model has a 6.5% higher peak load than the tests, which shows that the model and test are in good agreement with the peak load. As mentioned in the failure mode section, bearing failure is and screw shear both occur at peak load, with screw shear controlling the post peak response of the connection.
Figure 41: 6843 model vs test results

Table 11: Model and test stiffness comparison for 6843 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>7.09</td>
<td>6.04</td>
<td>5.40</td>
<td>5.41</td>
</tr>
<tr>
<td>80</td>
<td>2.52</td>
<td>2.38</td>
<td>2.25</td>
<td>3.61</td>
</tr>
<tr>
<td>100</td>
<td>0.74</td>
<td>0.75</td>
<td>0.73</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The model shows very good agreement with the test results for the connection stiffness. The 40% stiffness is higher than the tests, but the peak load, 80% and 100% stiffness of the model are close in value to the tests.
The 9733 tests had an average peak load of 4.34kN. The peak load of the model was 23% higher at 5.35kN. The peak load of the model is very inaccurate compared to the tests. Though the peak load could have been made lower, the connection stiffness and failure mode also became inaccurate when the model was refined to improve the peak load accuracy. No post-peak behavior could be captured in this model due to the contact parameter calibration conducted to improve the accuracy of the connection stiffness. When the default contact behavior was used instead, post-peak degradation was captured, but resulted in very high connection stiffness compared to the current 9733 model.
Table 12: Model and test stiffness comparison for 9733 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
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<tbody>
<tr>
<td>40</td>
<td>3.50</td>
<td>3.11</td>
<td>2.51</td>
<td>2.82</td>
</tr>
<tr>
<td>80</td>
<td>1.36</td>
<td>1.00</td>
<td>1.33</td>
<td>2.29</td>
</tr>
<tr>
<td>100</td>
<td>0.32</td>
<td>0.79</td>
<td>0.46</td>
<td>0.30</td>
</tr>
</tbody>
</table>

As shown in Figure 42 and Table 12, the stiffness of the model has very good agreement with the tests. The 40% model stiffness is slightly higher than the tests but is otherwise very accurate.
5.2. Parametric study of contact properties used to create robust model

The nonlinear penalty parameters for hard normal contact have the most significant effect on the connection stiffness for the models. The sensitivity of the models to these parameters will be examined in this section.

5.2.1. Maximum Contact Stiffness

The maximum contact stiffness $K_f$ affects three things in the model: the run time (or final displacement), the peak load, and the connection stiffness. Models that use the default $K_f$ can withstand the highest final displacement before the model aborts. This is because the default max contact stiffness is very high to minimize penetration, which is the goal of the hard contact relationship. The lower $K_f$ is, the lower the final displacement of a given model. Therefore, $K_f$ must be sufficiently high to allow for the model to have a high final displacement. A comparison of the effect of the max contact stiffness is shown in Figure 43. When the default $K_f$ is used, the model runs until 5.29mm, while final displacement ranges from 3.63-3.83mm for the lower to higher user input contact stiffness. The “low” $K_f$ was 20,000 N/mm, the “medium” $K_f$ was 40,000N/mm, and the “high” $K_f$ was 140,000N/mm. It can also be seen that the high $K_f$ had a higher final displacement (3.83mm) than the low (3.63) and medium (3.74mm) $K_f$ values. This comparison was conducted with all other contact parameters remaining constant, showing that the change to the contact stiffness was the only influence.
As previously mentioned, $K_f$ also influences the peak load. Using the default $K_f$ results in the highest peak load. Using the ‘high” $K_f$ results in a higher peak load than the medium, and the medium $K_f$ has a higher peak load than the lower $K_f$, as shown in Figure 44.

Figure 43: Comparison of length of run with an increase to $K_f$ for 4343 model
Figure 44: Comparison of peak load with increase to $K_f$ for 4343 model

Finally, the connection stiffness of the model is also affected by $K_f$. Other contact parameters can be used to control this effect on the connection stiffness which will be discussed in a later section. Unless controlled, increasing the $K_f$ can result in an overly stiff model, as shown by Figure 45. The default $K_f$ results in the model with the highest connection stiffness, and the low $K_f$ of 2000 results in the least stiff model. The higher max contact stiffness of 10,000 results in a significantly higher connection stiffness than the low stiffness model. Also, it should be noted that the models in Figure 45 have much lower final displacements than the models of Figure 43 and Figure 44, which makes sense due to Figure 45 having $K_f$ values used that are much lower than Figure 43 and Figure 44.
It should also be noted that there appears to be an upper bound to the effect of $K_f$. When other contact parameters have not been controlled, like in Figure 45, a change to $K_f$ always has a strong effect on the peak load, run time, and connection stiffness of the model. Figure 43 and Figure 44 have significant changes to the other parameters ($e$, $d$, and the initial contact stiffness $K_i$). Changing those parameters can cause the effect of $K_f$ to be less significant after $K_f$ is at a certain value. The max $K_f$ where this parameter still has a significant effect on the connection behavior of the model was found to vary with each model.
5.2.2. Initial Contact Stiffness
The initial contact stiffness $K_i$ selected in the models is based on the 40% connection stiffness. When $K_i$ is made higher, the 40% connection stiffness will increase, and if $K_i$ is made lower, the 40% connection stiffness decreases. This can be seen in Figure 46. When the “low” $K_i$ is increased from 2250 N/mm to the “high” $K_i$ of 3600N/mm, the connection stiffness also increased from 6.86kN/mm to 9.01kN/mm. When using nonlinear penalty contact definitions, the initial contact stiffness is controlled with the initial/final stiffness ratio in Abaqus. Therefore, regardless of changes to the max contact stiffness, the $K_i$ can be made the same by adjusting the initial/final contact stiffness ratio accordingly.

Figure 46: Comparison of connection stiffness with increase to $K_i$ for 4343 model
5.2.3. Lower and Upper Quadratic Limits

The lower and upper quadratic limits are parameters referred to as \( e \) and \( d \) in Abaqus. As shown in Figure 10, these two parameters determine the amount of penetration that is allowed between two surfaces in contact. The lower quadratic limit \( e \) is the amount of penetration allowed before the contact stiffness begins to increase from the initial contact stiffness \( K_i \). The upper quadratic limit \( d \) is the amount of penetration allowed before the maximum contact stiffness \( K_f \) is reached.

The \( e \) and \( d \) parameters are controlled by scaling them relative to a “characteristic interface length” (Abaqus Analysis User’s Guide 2014) calculated automatically by Abaqus. The characteristic interface length cannot be changed. The value is calculated based on the sizes of the elements that are in contact.

The \( d \) parameter is controlled by multiplying the characteristic interface length in Abaqus by a scale factor, known as the “upper quadratic limit scale factor”. The \( d \) parameter is the product of the upper quadratic limit scale factor and the characteristic interface length. Because the goal of hard contact is to minimize penetration between contact surfaces, the default for the upper quadratic limit scale factor is 0.03, which results in a low penetration.

To control \( K \) to result in an acceptable connection stiffness, \( d \) must be increased. A high \( d \) increases the amount of penetration allowed during contact, which is the opposite of what is ideal in a hard contact relationship. If \( d \) is too high, the final displacement before the model aborts will be inadequately small. However, a \( d \) higher than the default has a positive effect on the longevity of the correct connection stiffness. Therefore, \( d \) must be carefully chosen to ensure an optimal connection stiffness and to capture a satisfactory amount of post-peak degradation. In Figure 47, the effect of \( d \) can be seen. The “low”, “medium”, and “high” \( d \) all have a \( K_f \) of 20,000 and the same other contact parameters except for \( d \). Low, medium, and high \( d \) refer to upper quadratic
limit scale factors of 0.2, 0.35, and 0.5, respectively. At the beginning of loading, all three models have the same connection stiffness. The low $d$ model deviates from this initial stiffness the earliest, and shows a noticeably higher connection stiffness (due to $K_f$) from after it deviates from the initial connection stiffness. The medium $d$ deviates from the high $d$ connection stiffness at a much later time. Here, the high $d$ value of 0.5 is the best value. The point of deviation in the initial connection stiffness is how $d$ “controls” $K_f$. When $d$ is low, the contact stiffness $K$ increases from $K_i$ to $K_f$ quickly, which means that the connection stiffness visibly increases at a point before the connection behavior begins to soften. When $d$ is higher, $K$ increases from $K_i$ to $K_f$ at a later point. If $d$ is high enough, such as the “medium” and “high” $d$ in Figure 47, the connection behavior will naturally soften before the connection stiffness would increase due to $K_f$. This is why the “low” $d$ curve in Figure 47 has a jagged force-displacement curve compared to the smooth curves of the “medium” and “high” $d$ values. Also, note how the low $d$ has the highest final displacement, and the high $d$ has the lowest final displacement, as expected.

Although it appears that $d$ also has an influence on the peak load, this is due more so to the point of deviation in the initial connection stiffness. If $d$ is low, the model will be able to have a high connection stiffness earlier. A higher connection stiffness is what results in a higher peak load, so a low $d$ only increases peak load indirectly.
Figure 47: Comparison of effect of upper quadratic limit on 4343 model

The $e$ parameter is controlled in Abaqus through the “lower quadratic limit ratio”. This ratio is $e/d$, and based on Figure 10, must be less than 1, since that would make $e$ equal to $d$. Once the penetration exceeds $e$, the contact stiffness $K$ begins to increase. $K$ will increase until it reaches the $K_f$ at penetration $d$. A high $e$ results in $K_i$ occurring for a longer time before the increase to the $K_f$ begins. In Figure 48, the low $e$ is 67% of $d$, and the higher $e$ is 99% of $d$. Both have the same $K_i$, but the connection stiffness of the low $e$ curve shows a sharp stiffness increase at 0.13mm, while the high $e$ plot does not have that increase in connection stiffness occur until later on at 0.18mm. The increase in stiffness occurring later in the high $e$ plot is a direct effect of the higher value of $e$, as all other parameters are the same for the low and high $e$ plots.
When using the default contact stiffness properties, the peak load tends to have good agreement with the tests, despite its overly stiff connection behavior. By using appropriate values for $e$, $d$ and the initial contact stiffness, the effects of $K_f$ can be controlled to prevent an overly high connection stiffness while still capturing a sufficient amount of post-peak degradation in the model and maintaining an acceptable peak load.

5.3. Comparison of model and test results to AISI

The American Iron and Steel Institute (AISI) published equations to calculate the connection strength of screw fastened connections in their 2016 “North American Specification for the Design of Cold-Formed Steel Structural Members”. These equations are from section J4.3 of the
specification, where \( t \) is the thickness of Ply 1 or 2, \( d \) is the diameter of the screw, and \( F_u \) is the ultimate tensile strength of the ply. The subscript 1 or 2 indicates the ply used for each variable. Both the models and Pham and Moen’s tests showed that AISI’s equations only showed good agreement with tests that had tilting dominated failure. Equation 5 below is the tilting failure equation. Using this equation, the peak load for the 3333 ply configuration should be 2.88kN, and 4.47kN for the 4343 ply configuration, and the tests and models for these ply configurations both had peak loads of similar values.

\[
P_{nv} = 4.2\sqrt{\frac{t^2}{d}} F_{u2}
\]  

(5)

When Ply 2 has a thickness between 1-2.5 times the thickness of Ply 1, the peak load (strength of the connection) is supposed to be interpolated between equation 5 and the bearing failure equations from section J4.3 shown in equations 6 and 7.

\[
P_{nv} = 2.7t_1 d F_{u1}
\]  

(6)

\[
P_{nv} = 2.7t_2 d F_{u2}
\]  

(7)

However, when interpolation is required, the peak load due to tilting from AISI is less reliable. 4354 and 4368 are the two other ply configurations tested that had tilting dominated failure. By interpolating between the tilting and the minimum bearing strength found from Equations 5-7, the peak load for these two tests should be at 7.35kN and 9.31kN respectively. The average peak load of these tests was 5.54kN and 6.28kN, significantly lower than AISI. Per Corner’s (2014) analysis of these tests, these tests failed primarily by tilting, since the screw eventually pulled out of one of the plies. This matches the models, where for both the 4354 and 4368, the plies began to have significant separation. AISI’s interpolation method implies that when \( t_2/t_1 \) is close to 1.0, the tilting has a stronger effect on the connection strength than bearing. Though this concept
holds true for the 4368 and 4354 tests and models, the peak load from the interpolation is still significantly higher than the actual peak load recorded from the tests. Though the Abaqus models tend to have inaccurate peak loads for ply configurations with differing thicknesses, the models are much closer in peak load than AISI.

The 3368 ply configuration also had tilting and bearing at peak load like 4354 and 4368, but eventually failed by bearing of Ply 1 instead of tilting. The 3368 tests had an average peak load of 4.06kN, and a standard deviation of 1.54kN. Because 3368 has a $t_2/t_1$ thickness between 1-2.5, the peak load value is found by interpolating between tilting and bearing for AISI. By interpolating equations 5-7, the peak load should be 6.44kN, which is significantly higher than both the average peak load, even with the standard deviation. Based on the tests and the Abaqus model, the peak load should be based on a combination of tilting and bearing, so though the idea of interpolation is correct, the peak load is still very inaccurate.

The AISI results for the 3368, 4354, and 4368 ply configurations suggest that the interpolation method used to find the peak load when $t_2/t_1$ is between 1-2.5 is consistently incorrect, while the Abaqus models of these ply configurations produce more accurate results.

The 9733 and 4397 ply configurations had significant bearing of the thinner plies at peak load in the tests. This is also reflected in the Abaqus models of these ply configurations. The average peak load of these tests was 4.34kN and 7.62kN respectively. Using AISI, the peak load of these tests should be 2.83kN and 9.05kN. AISI’s peak load for the 9733 ply configuration assumes that tilting failure controls solely due to ply 2, but this is inaccurate. The bearing failure value found using equation 7 gives a value of 4.29kN, which is more in line with the actual behavior of the tests. However, because AISI bases failure for $t_2/t_1$ ratios of less than 1 on the smallest value of equations 5-7, it gives an incorrect value.
The 4397 ply configuration has $t_2/t_1$ of 2.14 and thus requires interpolation between equations 5-7 per AISI. However, the tests and the model both show that bearing of ply 1 is what occurs at peak load, and not a combination of tilting and bearing. This is further confirmation that the interpolation method presented in AISI does not accurately determine peak load.

The remaining ply configurations failed due to screw shear. These are 5454, 6843, and 9797. With these ply configurations, the AISI equations should show tilting and bearing failure values that exceed screw shear for AISI to be accurate. For 5454, screw tilting from AISI is the lowest value of equations 5-7 with a value of 7.62kN. The published screw shear strength for the Simpson Strong-Tie X Screw is 7.23kN (2018). The peak load of the tests is 6.16kN, with the model giving a very similar value. As expected based on the screw shear and tilting values, the screw fails in shear, showing good agreement with the expected failure mode based on AISI and Simpson Strong-Tie. Though the failure mode is in good agreement, the actual value of the peak load from the test and the model is much lower than the listed values from AISI and Simpson Strong-Tie.

The 6843 has a $t_2/t_1$ less than 1, so no interpolation between equations 5-7 is necessary based on AISI. Instead, the equation that has the smallest value controls the strength. However, the smallest peak load from AISI is 4.53kN due to tilting, meaning that tilting controls over screw shear. The 6843 tests and model all failed in screw shear, showing that the Abaqus models made are more accurate than AISI in predicting the failure mode.

The 9797 ply configuration had good agreement with AISI. The AISI tilting and bearing equations gave peak loads of 19.16kN and 16.95kN, significantly higher than the screw shear peak load from Simpson Strong-Tie. Therefore, AISI accurately predicts the failure mode of this ply configuration.
Overall, it should be noted that AISI’s equations for the peak load of these connections are only successful when the thickness of ply 1 and ply 2 are equal. For tilting and shear the equations successfully predict the failure mode and peak load. When the thickness of ply 1 and ply 2 vary, AISI’s equations are not reliable. The interpolation method recommended to determine the peak load is consistently incorrect compared to the tests. Because bearing failure is much more likely to occur when ply 1 and ply 2 are different thicknesses, this means that the interpolation method also fails to consistently predict bearing failure.

The Abaqus models presented in this thesis produce much more accurate results. The behavior and failure mode of the models always matched Pham and Moen’s tests, even when ply 1 and 2 have different thicknesses. The peak load for the models also showed slightly better agreement with Pham and Moen’s tests overall, while AISI’s equations only showed good agreement when ply 1 thickness equaled ply 2. Also, the tests and the models showed that having different ply 1 and ply 2 thicknesses sometimes resulted in the final displacement of a ply configuration having a different failure mode than at peak load, such as the 9733 configuration. This configuration had the bearing limit state at peak load but failed by screw shear at its final displacement. It is not possible for the current equations to capture this interaction between different failure modes, making the Abaqus models beneficial when determining screw connection behavior.

5.4. Future Work
More investigation into the Abaqus models made for the thesis is required before models can be built that do not require test data for validation. Though this investigation is yet to be conducted, consistent themes observed in the behavior of the connections and the models can be used to begin building those models. These themes are discussed in the sections 5.4.1-5.4.3. These sections also feature preliminary methods that can be used to validate the peak load, failure
mode, and connection stiffness of models without test data. The post-peak behavior of the models also requires further research. Work is necessary to determine how to consistently capture and understand post-peak degradation behavior for any model.

As discussed in the section 5.3, the current AISI connection strength equations produce inaccurate peak load and failure mode results when ply 1 and ply 2 have different thicknesses. Though the models can reliably produce the correct failure mode, further investigation into their peak load behavior when ply 1 and ply 2 have different thicknesses is required in the future. By completing this work, the models will be able to predict screw connection behavior much more accurately and consistently than AISI. Following this, improvements can then be made to AISI’s equations and failure mode determination in the future based entirely on the model results.

Once future work has been completed to understand the peak load, post-peak behavior, and to resolve or understand any inconsistencies in model behavior, rules of thumb can be specified for the method of modeling screw fastened connections. These rules of thumb can allow for a wide range of screw sizes and ply configurations to be modeled and validated.

5.4.1. Failure Modes
Prior to changing the contact parameters to obtain an accurate connection stiffness, each model in this thesis was first ran in Abaqus using the default hard contact with no changes to the nonlinear penalty contact parameters. This was found to be the best way to determine the true failure mode of the model, with the same criteria used to judge tilting, bearing, and screw shear failure from section 4.8 being used to define the failure mode. “True” refers to the model’s response when contact behavior is not softened with nonlinear penalty contact parameters. Softening the contact behavior with these parameters allows for accurate connection stiffness, but also can inadvertently affect the failure mode and peak load of the model. Therefore, by
comparing the behavior of models with user input nonlinear penalty contact parameters to default parameter models, the parameters can be set to ensure that the failure mode and peak load do not undergo any significant changes due to the parameters. For example, models that fail by screw shear neglect the tilting angle of the screw when determining the failure mode. If the contact parameters are changed in a way that prevents the model from meeting the screw shear failure criteria, the tilting angle could falsely predict the tilting failure mode since the screw behavior no longer indicates that shear should occur.

Every model run with the default contact properties had the correct failure mode validated by Pham and Moen’s tests, and this includes models such as 5454 and 9733, despite the fact that the changing of the contact parameters caused the failure mode of the final iteration of these models to change or become less apparent. Therefore, to determine the failure mode of a model without test data, a model should be run first that uses the default contact properties. Since the failure mode of this default model should be correct based on the results of this thesis, the contact parameters for the final iteration of this model can then be changed as needed in ways that can maintain the true failure mode of the model.

5.4.2. Peak Load
As mentioned in the previous section, changing the default contact parameters in a model can inadvertently change the peak load of a model. The peak load found with default hard contact is always higher than the peak load found after the connection stiffness has been reduced in the model. Based on the models validated by Pham and Moen (2015), the default peak load was usually less than 10% higher than the peak load found after refining the connection stiffness of the model. The only exception to this was the 4368 model, where refining the connection stiffness caused the peak load to drop by 20%. Since only one of the ten models had the severe
20% drop in peak load, running the model with default hard contact should produce an adequate estimate of the peak load of the connection before work is done to change the connection stiffness in the model.

5.4.3. Connection Stiffness
To validate the stiffness of models with no tests, an analysis of the stiffnesses of Pham and Moen’s tests is required.

Based on the stiffness characterization of Pham and Moen’s tests, the thickness of the plies had the main effect on the stiffness of the connections. The general effect of ply thickness can be shown by comparing the 40% stiffnesses of ply configurations with equal ply 1 and 2 thicknesses. The 3333, 5454, and 9797 ply configurations have an average 40% stiffness in the tests of 4.21kN/mm, 9.11kN/mm, and 30.45kN/mm. It can be seen here that as the ply thickness increases, the 40% stiffness also increases.

When ply 1 and 2 vary in thickness, ply 1 has the strongest effect on the stiffness. The 4343, 4354, 4368, and 4397 models had average 40% connection stiffnesses of 8.05, 8.29, 8.78, and 9.28kN/mm. This means that despite ply 2 becoming over twice as thick as ply 1 when comparing the 4343 test to the 4397 test, the 40% stiffness only increased by 15% due to ply 1 staying constant.

It should also be noted that this effect of ply 1 is only true when ply 1 is thinner than ply 2. It appears that when ply 2 is thinner than ply 1, it causes a decrease in the 40% stiffness. For example, the 9733 ply configuration had an average 40% stiffness of 2.81kN/mm in the tests, which is lower than even the 3333 ply configuration. The 6843 ply configuration had an average 40% stiffness of 5.62kN/mm, which is lower than both the 4343 and the 4368 ply configurations.
Based on the above analysis, for future models that cannot be validated with tests, the 40% stiffness should be based on the typical stiffness due to ply 1. For example, all models with a ply 1 of 43 mils had very similar 40% stiffness values, so a new model with a ply 1 of 33 or 54 mils should aim for a stiffness close to the 3333 or 5454 models. The 3333 and 3368 ply configurations had 40% stiffness values of 4.21 and 4.65 kN/mm, so that method for determining the stiffness also can be proven to work through the tests.

Not enough tests were conducted to conclusively determine why ply 2 exceeding the thickness of ply 1 reduced the stiffness of the connections, but for new models, aiming for a stiffness below the typical stiffness expected for the ply 1 should be acceptable.

Finally, when determining the contact parameters to use to control the connection stiffness, the parameters should be changed based only on the 40% stiffness. The 80% and 100% stiffness occur after the force-displacement curve softens, and after softening occurs the contact parameters have little effect on the behavior of the model. Also, based on the validated models, an accurate 40% stiffness usually is sufficient to have an overall good agreement with the force-displacement curve of the model compared to the tests.

5.4.4. Modeling Improvements
The models of the 9797 and 4368 ply configuration both had issues with the behavior of their force-displacement curves. Since the issues with these models could not be resolved, work must be done in the future to improve their accuracy. A discussion of the specific issues of the two models is below.

The 9797, shown in Figure 49, had very poor agreement with the tests overall. Though the peak load and failure mode for this model have good agreement with the tests, the connection stiffness is inaccurate. This can be explained by comparing the force-displacement curves for the tests and
the model. The behavior in the tests is difficult to replicate with the process used in the models. The 40% stiffness of the tests is very high and then significantly softens by the 80% stiffness. The point of yield in the ply, indicated by the horizontal dash-dot line in Figure 49, does not align with the softening point that occurs much earlier in the 9797 tests. Because the reason for the softening in these tests is not yet known, any methods normally used to achieve the stiffness in this thesis will result in either the 40% or 80% stiffness being incorrect compared to the tests. Table 13 shows that the 40% and 80% stiffness are almost identical in the model, and an attempt to increase these stiffnesses would only result in a higher peak load.
Figure 49: 9797 model results vs test results

Table 13: Model and test stiffness comparison for 9797 ply configuration

<table>
<thead>
<tr>
<th>% of Peak Load</th>
<th>Model (kN/mm)</th>
<th>Test 1 (kN/mm)</th>
<th>Test 2 (kN/mm)</th>
<th>Test 3 (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>3.22</td>
<td>26.09</td>
<td>20.83</td>
<td>44.44</td>
</tr>
<tr>
<td>80</td>
<td>3.23</td>
<td>7.99</td>
<td>5.93</td>
<td>6.81</td>
</tr>
<tr>
<td>100</td>
<td>1.38</td>
<td>2.62</td>
<td>3.50</td>
<td>2.81</td>
</tr>
</tbody>
</table>

For the 4368 model, the connection stiffness showed very good agreement with the overall stiffness of the tests, as seen by Figure 38. However, the peak load of the model is 33% lower than the tests. Even if the hard contact settings are at their defaults, as discussed in section 5.4.2, the peak load was still much lower than the tests. Considering also that the 6843 model had very
good agreement with the peak load of the tests, this issue with the peak load cannot be simply explained.

The post-peak behavior of the 4368 model is also not well understood. Based on the model behavior shown in Figure 23, the behavior of the connection fails by tilting. However, the 4368 behavior of the force-displacement curve does not align with tilting or with any other post-peak force-displacement curve behavior observed in the other models.
CHAPTER 6

CONCLUSION

The goal of this work was to build a finite element model that could successfully replicate the behavior of cold-formed steel single lap screw fastened connections. To validate the model, tests of screw-fastened connections by Pham and Moen (2015) were compared to models with the same ply configurations. A validated model will have a peak load, stiffness, and failure mode that match the results published by Pham and Moen.

For the ply configurations where ply 1 and ply 2 had the same thickness, the model was successful. The peak load of the models matched the tests with a maximum percent error of 10.5%. Almost all these models had the same failure mode as in Pham and Moen’s tests. For one model, the 5454 model, the failure mode of the model differed from the test, but further examination of the screw showed that the model was very close to reaching the failure mode of the tests. The overall connection stiffness behavior for all these models also had good agreement with the tests.

For the ply configurations where ply 1 and ply 2 had a different thickness, the models matched the failure mode and the overall connection stiffness behavior of the tests fairly successfully. The peak load had mostly poor agreement, with a maximum percent error of 33% for the peak load of the models in this group compared to the tests.

The contact behavior was found to have a strong effect on the stiffness of the connections modeled. The contact of the screw and the hole in the normal direction required refinement for each model. To determine how the contact parameters should be changed for each model, a parametric study was conducted. This study showed how each normal direction contact parameter affected
the connection stiffness. Based on the results of the parametric study, a trial and error approach was used to determine the best contact parameters for each model that allow the correct peak load and the failure mode to also be maintained.

A comparison of the model results, Pham and Moen’s test results, and the AISI equations from section J4.3 of the 2016 Cold-Formed Steel Specification was also conducted. This showed that overall for the models created, the models show better agreement than AISI. AISI’s equations show good agreement with the peak load and failure mode of Pham and Moen’s tests when ply 1 and ply 2 are equal thicknesses, but fail when ply 1 and ply 2 have different thicknesses. The Abaqus models consistently show acceptable agreement of the failure mode regardless of the ply configuration, so the Abaqus models work better than the AISI equations.

Except for the one model, the post peak behavior of the force-displacement curve reveals the failure mode of the model. The force-displacement curve and the failure mode criteria determined in the thesis aid in the beginning of the work to predict the response of models that cannot be validated with test results. In the future, more work needs to be done to refine the models with different ply 1 and ply 2 thicknesses. The final goal of this research is to have a consistent modeling regime that gives acceptable results for the stiffness, peak load, and the failure mode, and the work published in this thesis is the first step in making that possible.
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