# Experimental Study of Cold Formed Steel Roof Truss Connections

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Master of Science In

Civil and Environmental Engineering

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By

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

"Experimental Study of Cold Formed Steel Roof Truss Connections" presented by Nikita Lazarev,

a candidate for the degree of Master of Science in Civil and Environmental Engineering, and hereby certify that, in their opinion, it is worthy of acceptance.

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# Abstract

Cold-formed steel (CFS) roof trusses are commonly used due to their cost effectiveness, reliability, and high stiffness to weight ratio. To increase the effectiveness of these widely used trusses, the overall research project aims at evaluating the response of CFS roof trusses under static and dynamic loads resulting from an external blast. Numerical simulations models of full-scale CFS roof trusses are performed and validated using full-scale CFS truss experiments in the lab and in the field. To improve the simulation predictions, the accurate response of the connections will need to be incorporated into the numerical models. Since connection related failures are common in such trusses, and to improve the understanding of the full-scale truss response, it is necessary to study the response, including failure modes, of such connections. Therefore, the objective of this thesis is to experimentally study the response of CFS truss connections of cold formed steel roof trusses. Material response, including modulus of elasticity, yield stress and strain, and ultimate stress and strain, were also evaluated in this thesis. The connection testing included the evaluation of connections with varying member types, number of screws, and screw spacing. The results included stiffness, deflection, and load capacities. Conclusions were made for several key subjects as follows. The cold rolling process results in changes to material properties that result in decreased ductility. Increasing the number of screws increases load capacity and stiffness. Decreased screw spacing causes a group concentration effect that reduces load and stiffness of the connection in proportion to number of screws. Connections exhibit bearing & tearing, tilting, pull-out, block shear and shearing of screws failures. The web member composing the end bearing connections had a drastic impact on the performance of the end bearing connection.

# 1 Introduction

## 1.1 Background

The Structural Engineering industry aims to create stronger, safer and more cost-efficient structures and structural components. This leads to a need for a material that is cost effective, reliable and has a high stiffness to weight ratio. Also, over the past several decades, there has been a sharp increase in explosion threats to some building structures. Cold-Formed Steel (CFS) is commonly used for building envelope, including walls and roof systems. Research has been performed on the response of CFS wall systems under blast loads, but very limited research exists for CFS truss systems. Therefore, additional research on the response of CFS roof truss systems under static and dynamic loads is still needed. To advance this research area, numerical models are needed to support experimental evaluation efforts of the full-scale CFS roof truss systems. The success of such numerical models depends on many main factors; one of which is the material and structural response of the connections. Therefore, the goal of this research is to experimentally study the various connection details used in CFS roof truss systems.

## 1.2 Objectives

The overall objective of the research is to evaluate the blast resistance of cold-formed steel roof trusses. Some efforts related to this were recently published [1]. To support the full-scale modeling and testing programs, material, connection, end-bearing responses, including failure modes, must be evaluated. These material characteristics, such as modulus of elasticity and yield stress and connection characteristics, such as stiffness and load capacity are critical inputs to the numerical models to enhance their accuracy.

## 1.3 Thesis Summary

The experimental study described in this thesis is focused on six different categories of tests: two types of materials; two types of truss connections; two types of end-bearing connections. The thesis consists of the following chapters:

- Chapter 1 is an introduction that covers background, objectives, and a summary.
- Chapter 2 is a literature review of related works.
- Chapter 3 describes the materials characterization test set-up, results, and analysis.
- Chapter 4 describes the test set-up, results, and analysis for Aiges CFS roof truss connections.
- Chapter 5 describes the test set-up, results, and analysis for TrusSteel CFS roof truss connections.
- Chapter 6 focuses on the test set-up, results, and analysis for select end-bearing connections.
- Chapter 7 summarized the conclusions and recommendations and future work for this research.

# 2 Literature Review

## 2.1 Preface

In this section, a literature review will be conducted on testing standards written by the American Society for Testing and Materials, previously conducted tests, and previously written papers. The review will be aimed at conducting research in two broader key areas, material testing and connection testing. The material testing section will be broken down into information over cold forming of steel, the process of creating test coupons and the test that we performed itself. The connection testing section will analyze the behavior of screws, types of failure, and the effect of the spacing and the number of screws has on the strength of the connection. A portion of this literature review will also analyze the work on full-scale CFS trusses by other members of our team. The goal of this literature review is to obtain vital data and information from previously conducted tests, so that we can strengthen the credibility of our tests, while also, adding new information to previously conducted work.

## 2.2 Material Testing

### 2.2.1 Test Procedure

The first test conducted was the testing of material characteristics of the cold formed steel trusses by performing a tension test. The material test was conducted using procedures from ASTM E8/E8M. This ASTM is the approved standard for testing materials made of metal in tension. The ASTM provides guidance on determining different material characteristics through the use of the tension test. The ASTM also specifies conditions at which the tests must be performed, such as, the room temperature and the dimensions of the coupon. Tests were performed within the range of 50 to 100 degrees Fahrenheit and using the dimensions of the subsize specimen as specified in the ASTM [2]. During the creation of the subsize specimen, a waterjet was used to cut the testing specimen out of the truss member. Previous testing and analysis was done on the effects on material characteristics from cutting stainless steel with a waterjet by Dominika Lehocka. This test found that the modulus of elasticity near where the waterjet cutting occurred and on the newly formed surface increased by 5-30 GPA [3]. This indicates an increase in modulus of elasticity of 2.5-15% that is caused by the use of the water jet. For our testing, we performed testing on cold formed steel rather than stainless steel, so there is uncertainty on the exact impact that the waterjet has on our material characteristics. The test performed in our studies did not focus on the effect of the waterjet on our material characteristics, but we are aware that there may be slight error when comparing the results of our subsize specimen to the material characteristics of the truss member due to the waterjet cutting based on the information found by Lehocka.

### 2.2.2 Material Information

Steel members have many important properties and exhibit different behaviors at different stages of loading. To capture these characteristics, a uniaxial tension test is typically performed in accordance to ASTM E8/E8M. When members are loaded in a uniaxial tension test, they have an initial stage of elasticity where "the … member deforms … based on the modulus of elasticity" [4]. The modulus of elasticity is the slope of the stress versus the strain in the elastic region. During this stage, the member has not yet yielded and no permanent deformation has occurred. At the conclusion of stage 1, the steel yields and the hardening stage begins [4]. Hardening is an inelastic behavior quantified by the hardening modulus. The hardening modulus ($E_h$) is the slope of stress over strain in the region between yielding and ultimate stress. Stage 2 concludes when the member reaches peak load. See Figure 1 for visual description of a typical stress strain curve of steel.

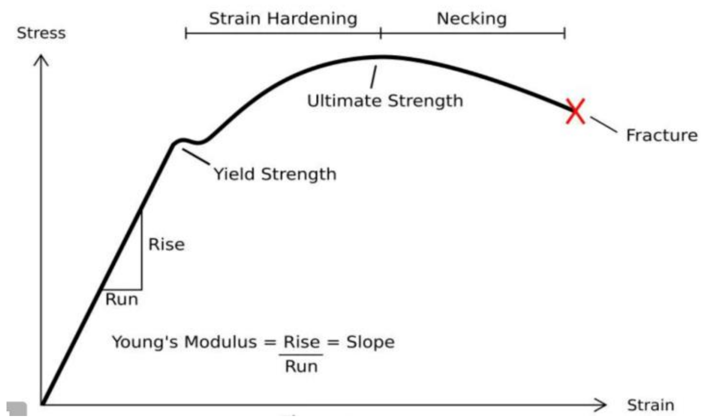



Figure 1: Stress Strain Curve

At peak load, post peak behavior begins and a localization zone forms. Immediately after the peak load, strain begins to concentrate in the localization zone and strain "outside the localization zone slows down until the bifurcation point is reached" [4]. At the bifurcation point, strain outside the localization zone begins to unload elastically. Figure 2 provides a graphical example of this phenomenon.

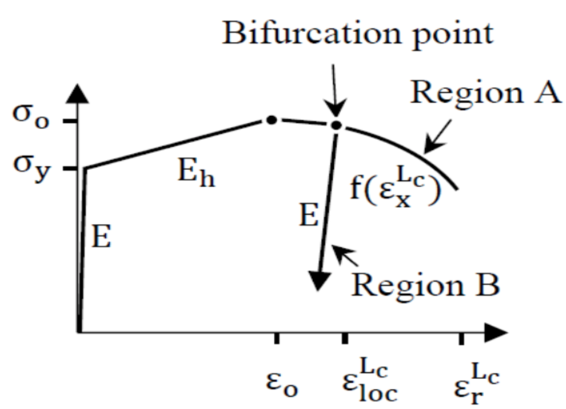



Figure 2: Altai, Orton, Chen Bifurcation Point [4]

Strain continues to localize in the localization zone until failure. The length of the localization zone is affected by the length of the specimen. “Longer specimens, … have longer localization lengths (and) have a steeper slope of the softening curve” [5]. Engineering strain is also affected by length of the specimen. See Figure 3 [4].

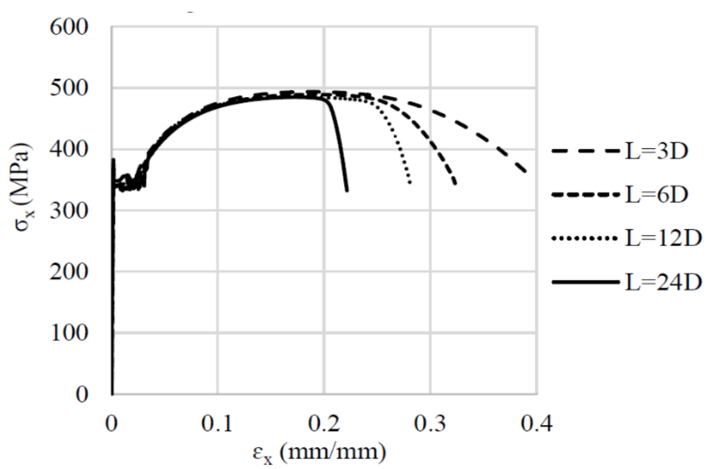



Figure 3: Length Effect on Engineering Strain [4]

This is important for selection and consistency of specimen sizes because the strain energy of the steel is very important for blast resistance.

Finally, Altai, Orton and Chen provide two more pieces of information. The first is that “members (that have) more … initial imperfection tend to experience softening earlier” [5]. This is a cause for variation and error between sample results. The second piece of information is a formula provided. “Externally applied load equals the product of incremental change in total displacement … and the stiffness of the member” [5]. This formula is a key formula for all testing that will be done within this report.

2.2.3 Cold Formed Steel Information

Steel has two main types of ways that it is commonly created, cold formed and hot rolled. These two forms offer different benefits and have different material properties. "Cold (formed) steel is processed at room temperature." This is far below "the recrystallization temperature of steel" [6]. The way the steel is formed creates important differences in material characteristics. The first important characteristic of cold formed steel is that "the yield strength of cold (formed) steel is higher than that of hot rolled steel" [7]. The yield strength, ultimate strength and hardness are "up to 20% greater … than hot rolled steel" [6]. The second important characteristic is that hot rolled steel has "increased ductility and toughness" over cold formed steel [7]. Both of these material characteristics come from the fact that, when forming "takes place in temperatures below the recrystallization temperature, strain hardening occurs (and) plastic deformation" is induced, causing yield strength to increase and ductility to decrease [7].

Abdel-Rahman and Sivakumaran performed testing on the material properties of cold-formed steel members. They studied the effects of the cold forming process on different locations throughout the steel member to determine the effects that the forming had on the material. They noticed "substantial changes in the material behavior … at and around the corner areas as a result of the large plastic deformations caused by the cold forming" process [8]. The material behavior changes where "considerable increases in the yield and ultimate strengths … at the corner areas" [8]. They also noticed very large reduction in ductility and the "disappearance of the yielding plateau and the strain hardening range" [8]. Also, "variation of residual stresses across the … sections" were found [8] Figure 4 shows the differences of the material behavior caused by the cold forming at different locations throughout the member.

The key takeaways from the articles and studies mentioned above are that cold forming changes material properties by increasing the yield and ultimate strength, while decreasing the ductility. This is vital information when understanding cold formed steel members. Also, when cold forming members, there may be significant changes in material properties at corner locations that we must be aware of and test for when testing material characteristics.

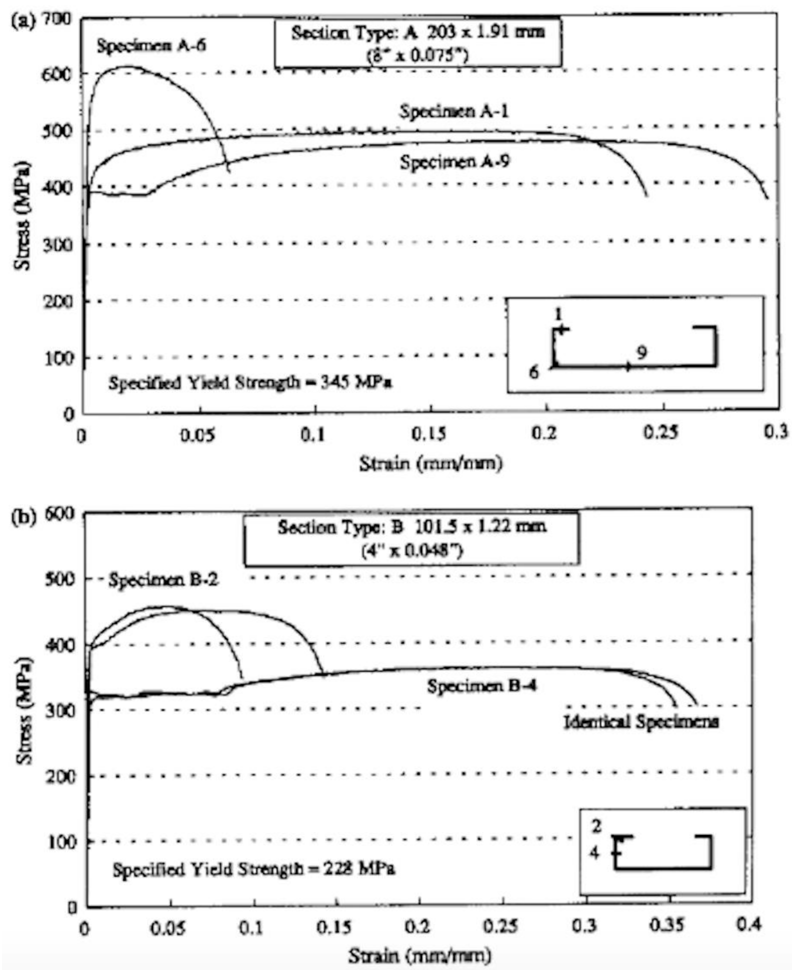



Figure 4: Abdel-Rahman and Sivakumaran Test Results [8]

## 2.3 Connection Testing

2.3.1 Screw Amount and Spacing

The connections between the members of the trusses are held together by self-tapping screws. The behavior and strength of the connection is highly dependent on the number and spacing of the screws in the connection. The American Iron and Steel Institute Design standard governs the design of Cold Formed Steel connections. AISI-2016 Section J3.1 establishes a governing minimum spacing requirement between centers of 3d (diameter) [9]**.** LaBoube and Sokol performed testing to analyze screw connections at spacing of 2d and 3d on normal ductility cold formed steel. Their tests determined that screw spacing of 3d created a group effect that reduced the connections strength in proportion to number of screws, hence, caused unconservative design. The equation in Figure 5 was developed to account for the group effect of screws on normal ductility CFS.

$$R = \left( 0.535 + \frac{0.467}{\sqrt{n}} \right) \leqslant 1.0 \qquad (3)$$

The design equation is limited to the following range of test parameters: $0.76\,\text{mm} \leqslant t \leqslant 1.35\,\text{mm}$, where $t$ = steel sheet thickness; $4.19\,\text{mm} \leqslant d \leqslant 5.46\,\text{mm}$, where $d$ = outer diameter of screw threads; $s \geqslant 3d$, where $s$ = center-to-center screw spacing; $347\,\text{MPa} \leqslant F_u \leqslant 482\,\text{MPa}$; and $1.19 \leqslant F_u/F_y \leqslant 1.62$.

Figure 5: Group Effect of Screw for Normal Ductility CFS [10]

Their tests also indicated that screw spacing of 2d had an even lower connection strength per screw then screw spacing of 3d due to the group effect being larger [10]. This indicates that as spacing between screws is decreased, a connection’s strength per screw also decreases when using normal ductility steel.

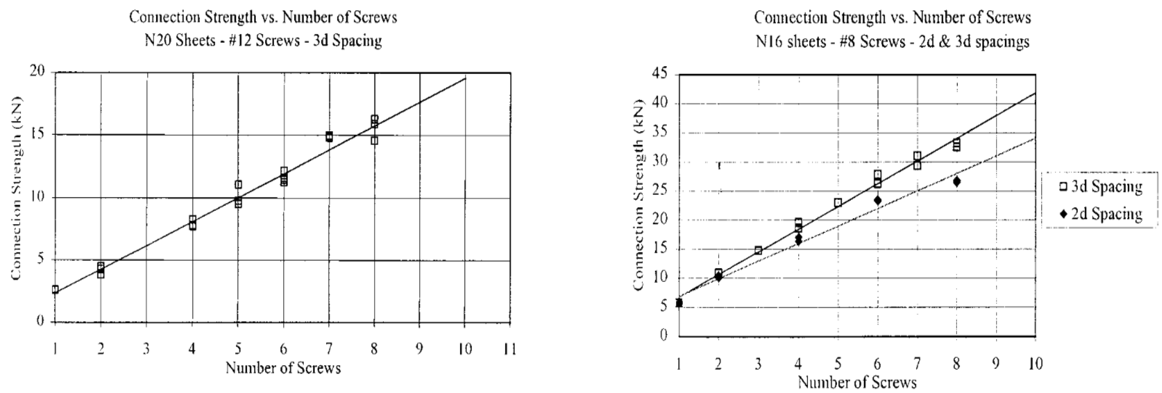
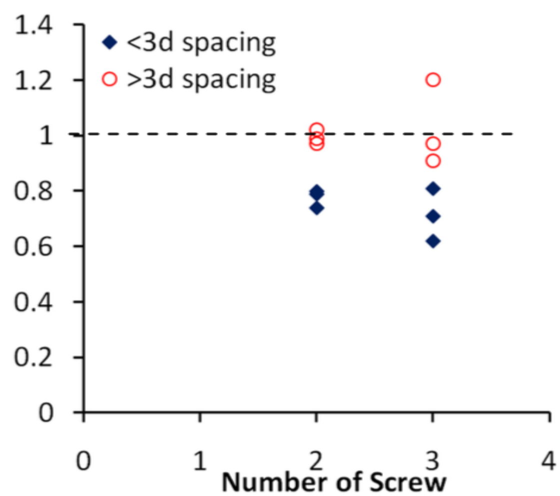



Figure 6: LaBoube & Sokol Normal Ductility Steel Results [10]

Fairuz and Hieng Ho also performed testing to analyze the effects of number of screws and screw spacing related to the American Iron and Steel Institute limiting spacing value of 3d. The tests of Fairuz and Hieng Ho were conducted on high strength low ductility steel. It was determined in their study that as number of screws increased, the connection strength increased proportionally to the amount of screws when spacing was greater than 3d. When spacing was less then 3d, connection strength did not increase proportionally to the number of screws and showed group reduction effect [11].




**(c) Effect of screw spacing on Multiple Screw**

Figure 7: Fairuz & Hieng Ho High Strength Low Ductility Steel Results [11]

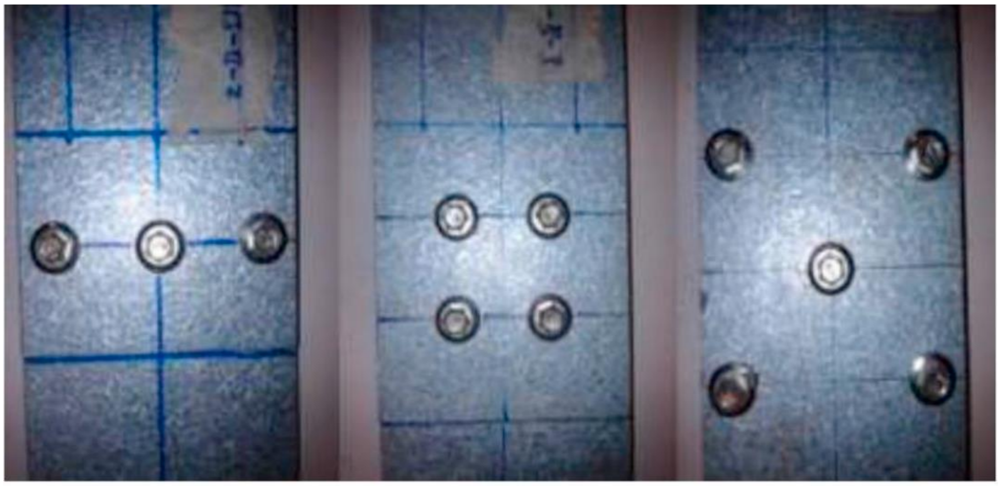
Lau and Tang also performed testing on the group effects of screws on high strength low ductility cold formed steel. They performed testing on the shear strength of single lap connections. Their results determined that low ductility steel was able to achieve 99% percent of the connection capacity, hence making the group effects negligible for low ductility steel [12].

The previously mentioned studies indicate a difference in behavior between normal ductility and low ductility steel when spacing of larger then 3d is used. However, regardless of the ductility of cold formed steel used, when spacing of less than 3d is used (i.e. 2d), a group reduction effect causes the strength of the connection to decrease in proportion to the number of screws. It is also likely, due to the trend from the aforementioned tests, that decreasing the spacing below 2d, will cause an even larger group reduction effect that will decrease the strength of the connection in proportion to number of screws even greater. We can conclude that low screw spacing will cause a group reduction effect that will cause premature failure of cold formed steel truss connections.

#### 2.3.2 Screw Pattern

Studies were also performed on the effects of screw pattern on strength of CFS screw connections. Laboube and Sokol performed testing on 27 different screw patterns to analyze the effects of the pattern on the connection strength. It was determined from the tests that group effect caused by different screw patterns "were within 7% of the average" connection strength. The results from Laboube and Sokol indicate that the varying screw pattern does not have significant impact on connection strength per bolt [10].

Another study on screw pattern of self-drilling screw connections for high strength cold-formed steel was also performed. Krishanu performed tests on 25 different variations of connections with 3 screw patterns, shown in Figure 8.



(a) 3 screws (b) 4 screws (c) 5 screws

Figure 8: Krishanu Screw Patterns [13]

The three patterns used are correlated to the amount of screws. The connection strength of the “3, 4 and 5 screw patterns are 5.95%, 1.52% and 3.91 lesser”, respectively, when comparing to the strength per screw [13]. The percentage differences are very similar to the work of Laboube and Sokol, who found that connection strength was within 7%. We can conclude from the results of both tests that screw pattern does not have a significant impact on the connection strength, but does have a minor effect of less than 7% that should be noted.

2.3.3 Failure Types

An important factor in analyzing the connection is the type of failure that occurs. There are several types of failures that can occur in CFS screw connections. Sivapathasundaram and Mahendran performed testing on CFS roofing systems and determined that two types of failures are the main causes of localized failures in connections. The failures are classified as "pull-through and pull-out failures" of the screw connections [14]. Testing determined that several factors affected the pull out capacity of a connection. "Material thickness and grade" along with "thread outer diameter, inner diameter, drill point diameter" and screw pitch, which is the distance between threads, governed pull-out failure capacity [14]. They found that a key factor in determining the pullout capacity of screw connections was the thickness of the material to screw pitch ratio. In their tests, when the thickness to screw pitch ratio exceeded 1, a pull-out failure without bending deformation occurred. When the thickness to pitch ratio was below one, a failure with significant bending deformation to the material occurred during the pull-out failure. In correlation to the previously mentioned findings, decreasing the pitch or increasing the material thickness will increase the pull out capacity [14].

Liu, Liu and Feng also performed testing on the behavior of screws on streel structures. In their testing, they found that "self-drilling screws have tilting tendency and such … tendency become more severe after increasing the applied loads" [15]. The testing performed by Liu, Liu and Feng found that typical failures included tilting failure and bearing failure. They found that "large plastic deformation" was found at the bearing locations of the steel plates resulting in bearing failure. They also found that with higher numbers of screws, tilting failure would create a situation where the heads of screws would be sheared off [15]. This work illustrates other types of failure that can be found in connections: tilting failure and bearing failure.

The work of Hongthong, Benchaphong, Benchanukrom and Konkong confirms the results of Liu, Liu and Feng. They performed testing on connections with one, two and four screws. There results found 3 types of failures: Bearing, Tilting and Shear. There work showed that typically for a one screw connection a bearing failure would occur in the material. For a two screw connection, a bearing and tilting failure would occur, followed occasionally be a shear off of one or two screws. For a four screw connection, it typically had bearing, tilting and shear failure of two of the four screws, but also had three screws and zero screws shear off. Their results match the results previously mentioned and confirm that Bearing and Tilting failures with occasional screw shear off for higher amounts of screws is a very common mode of failure for CFS screw connections [16].

Francka and LaBoube, in a separate study, performed further testing on types of failures of screw connections. They examined connections that had shear force and tension forces applied to them. The first important piece of data found is that edge stiffeners did not affect the strength of the connections. They also did not affect the failure mode of the connection. Second, Francka and LaBoube found that shear failure of the screws occurred in certain samples that were at 15 and 30 degree angles with large amounts of shear. They did not perform further study on this, but shear failure of screws is a noteworthy failure type. Third, they found that during pull out failure, each screw thread would pull out of the hole individually and the following thread would then catch the sheet. Fourth, they found several main types of failures occurred. Typically the connection had a "combination of … pull-out, tilting…, and bearing of the sheet" [17]. This is very similar to the types of failures found by the previously mentioned studies. Another important finding in the testing of Francka and LaBoube was that normal and low ductility specimens behave different when it comes to failure. Normal ductility specimens had more bearing deformation and tearing of the sheet failure. Low ductility typically exhibited more tilting failure, but still saw some plastic deformation [17]. The testing of Francka and LaBoube provides further information about the types of failures that occur in CFS Screw connections and provide us with the important piece of information that stiffeners do not affect the connection strength or failure type.

Yan, Mu, Xie and Yu also briefly discuss self-drilling screw failure. They found that 3 types of failures typically occurred in their tests. Failure type a was tilting and bearing failure, failure type b was shearing of the fastener and failure type c was shearing (tearing) of the top sheet [18]. Figure 9 shows the failures that occurred in their testing.

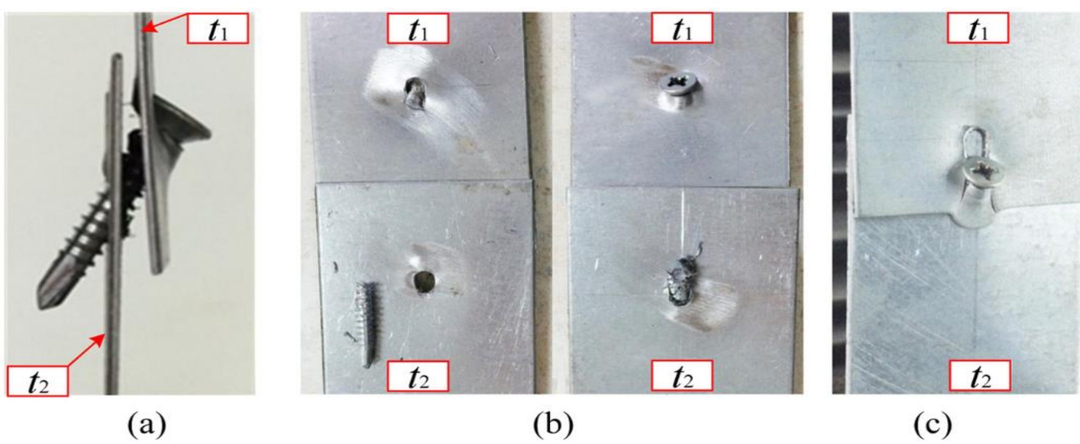



Figure 9: Yan, Mu, Xie and Yu Types of Failures [18]

Lastly, a final type of failure that may occur is block shear. Although not many studies have been done in regards to block shear failure of screw connections on metals, it is important to mention, as it is a possible type of failure. Block shear is a failure in tension and shear along a failure path between screws. Figure 10 is an example of how block shear may occur in a CFS screw connection [19].

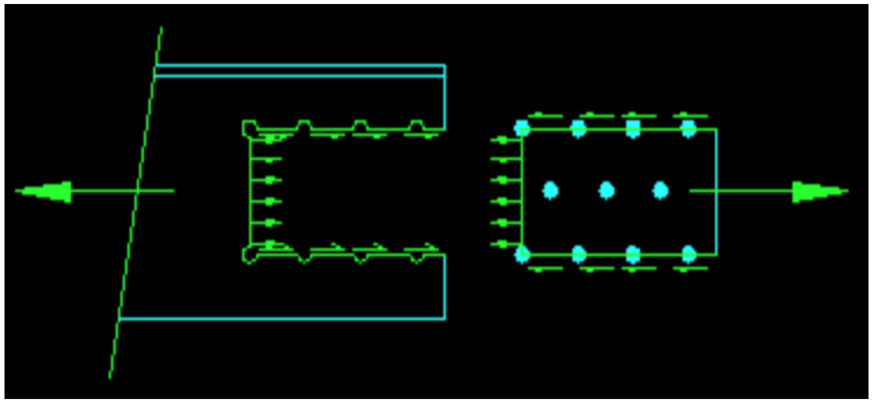


Figure 10: Block Shear Failure [19]

To conclude, screw connections have several failure types found in previous studies. Pull-out, pull-through, bearing and tearing, tilting, shear in the screw and block shear are all types of failures that a CFS screw connection may exhibit. Several factors, such as, the material, the screw, the screw spacing, the force angle and amount of screws affect that type of failure. Stiffeners do not affect the failure type.

## 2.4 Full-Scale CFS Truss Testing

David Treece performed testing on full-scale CFS roof trusses under quasi-static loading. He performed testing on three different types of Truss configurations and found different failure types occurred. Some of the failure types are related to the work done in this paper, and this literature review will focus on building on this aspect of David's work.

The first member tested was AG36-D35. In this member, there were partial failures in several connections throughout the member. "Screw… pull out of the vertical elements (and) tearing … around the screw holes" [1] where found in this test. Figure 11 shows pictures of partial failures that occurred in this test.


Figure 11: AG36-D35 Connection Failures – Treece [1]

There was also end bearing connection failure in AG36-D35. Treece found that an end bearing connection failed due to "screw shearing and pull-out between the tension chord and vertical" [1]. Global twisting also occurred in the end bearing connection causing the truss to remain "partially connected to the deformed clip angle that attached the specimen to the support" [1]. Figure 12 shows a visual of the end bearing failure occurring in AG36-D35.


Figure 12: Treece End Bearing Failure AG36-D35 [1]

The second test performed by Treece was on the AG48-D35 member. In this test, the main cause of failure was the rupture of a main diagonal. This rupture began at a screw hole and was due to “the chord to web connections … (not having) adequate screw spacing” [1]. Treece notes that the connection required higher amounts of screws to achieve the capacity requirements, but the screw spacing is not great enough. There was also a “connection failure between the tension chord and end vertical (that) displayed a mix of screw shearing and pull-out in the 9 screws" [1]. Also, a "chord experienced partial tearing … at joint QN" [1]. Figure 13 shows a visual of a connection failure occurring in this member.

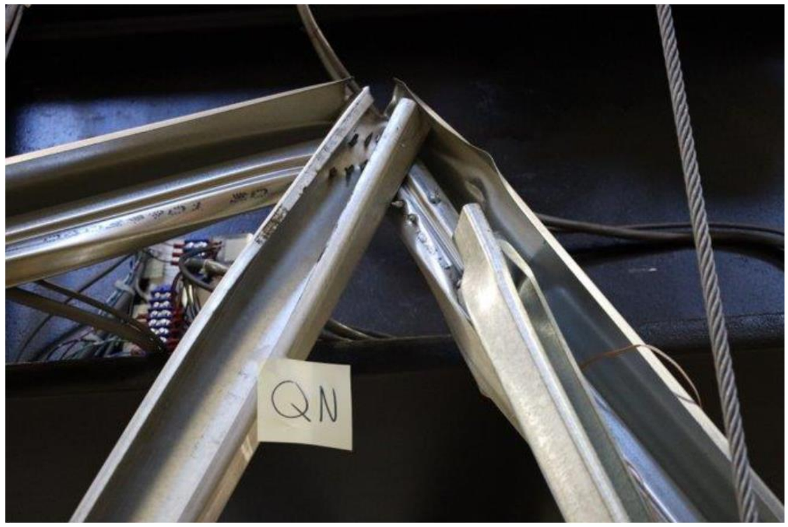



Figure 13: Connection Failures – AG48-D35 – Treece[1]

AG48-D35 also had failures occur at end bearing connections. Deformation occurred at the clip angles attached to verticals. Twisting of verticals were observed at end bearing connections. Truss deflection caused screws to be "eventually sheared in both sides of the East end bearing" [1]. Figure 14 shows end bearing failures that occurred in this member.

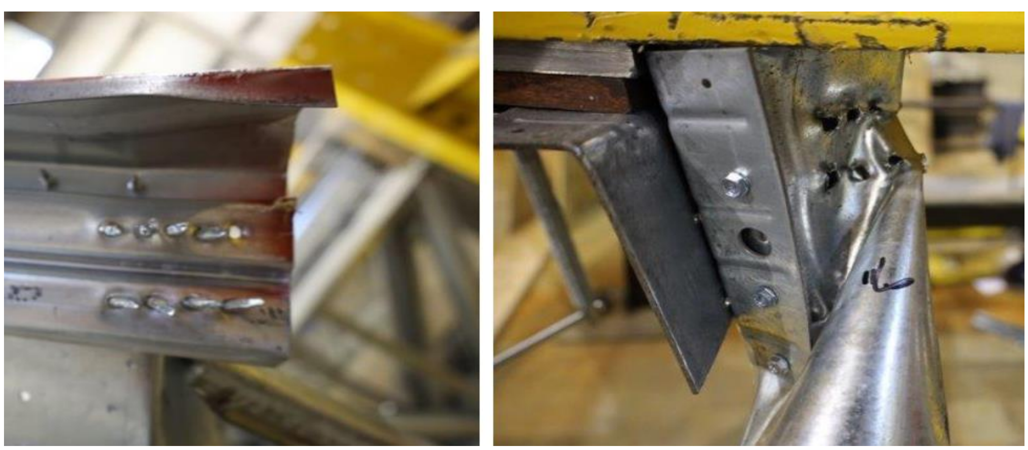


Figure 14: Treece End Bearing Failure AG48-D35[1]

The third member Treece performed testing on was the AG48-D57 truss. AG48-D57, similarly to the previous two tests, had connection failures and end bearing failures. "A partial failure in the connection with vertical B-Q" was caused by tension chord damage [1]. There were also shear failures at all end bearing connections. The "failure happened at all four screws connecting the chord with the clip angle" [1].

There are two main takeaways from the testing of the full-scale trusses done by Treece that relate to the work in this paper. First, several full-scale truss failures occur at connections, and these connections should be tested and potentially improved to build on the work performed by him. Second, full scale truss failures often occur at end bearing connections. These end bearing connections must also be tested and potentially improved.

# 3 Material Testing

## 3.1 Preface

The objective of this chapter is to test the material characteristics of two types of cold formed steel materials. These test results will allow us to obtain material characteristics and further information about the materials. We will also be able to input the material characteristics into numerical models. We will be performing a uniaxial tension test using an Electromechanical Tensile Test Machine. Two coupons from different parts of each component will be created and tested. This test will provide stress-strain curves that can then be used to pull important material characteristics off of. The test provided results such as the modulus of elasticity, yield stress, yield strain, ultimate stress, ultimate strain and other material characteristics. We will also make observations regarding the effect that location of the sample has on the material properties and the effects the cold forming process had on the material characteristics.

## 3.2 Research Method TrusSteel

### 3.2.1 Truss Members

The trusses that are being tested consist of 9 members. There are 4 chord members and 5 web members that vary by size and thickness. Different chord and web members are used in different trusses that are being tested. TSC sections are chord members, while W sections are web members. Shown on the following page are pictures showing the dimensions of chord and web members and how they differ from each other. Figure 15 is an example of the full-scale truss.

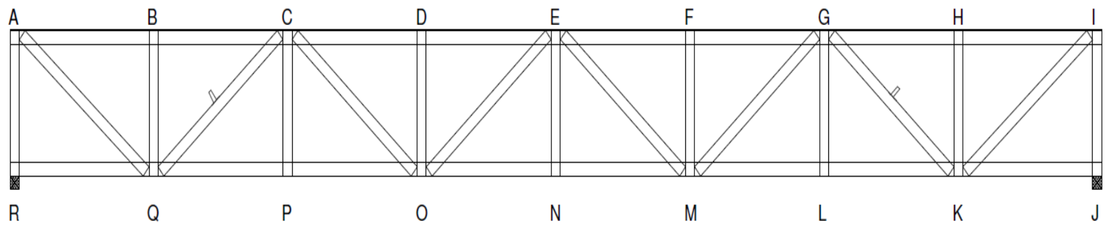



Figure 15: Full-Scale Truss

3.2.2 Test Location

Coupons will be created from two locations on each component of the truss. The first coupon will be from the center of the largest face, while the second coupon will be near an edge of the smaller face. Red arrows in Figure 16 will indicate the location of the two coupons from each component.

3.2.3 Chord Members

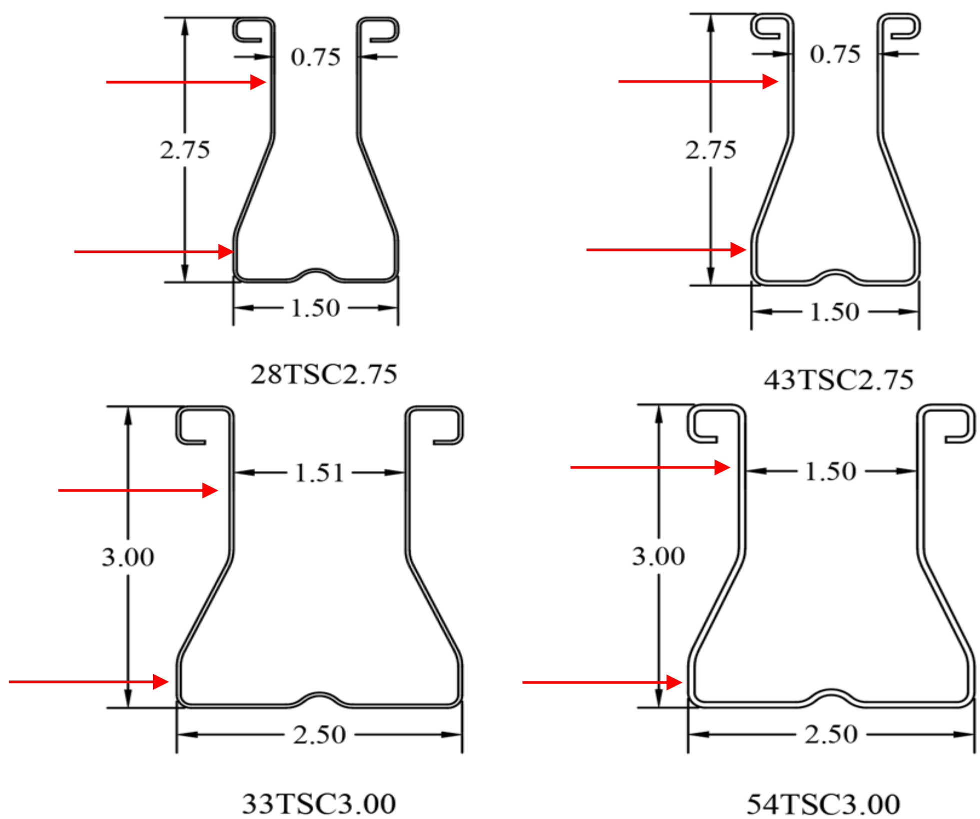



Figure 16: TrusSteel Chord Coupon Locations

As seen above, the TSC members are chord members that are differentiated by their heights and thicknesses in inches. The red arrows indicate the locations of each coupon. For the chord members, the top arrows point at the larger face coupon at the center of its face. The bottom arrows show the smaller face coupon that is near an edge.

<u>3.2.4 Web Members</u>

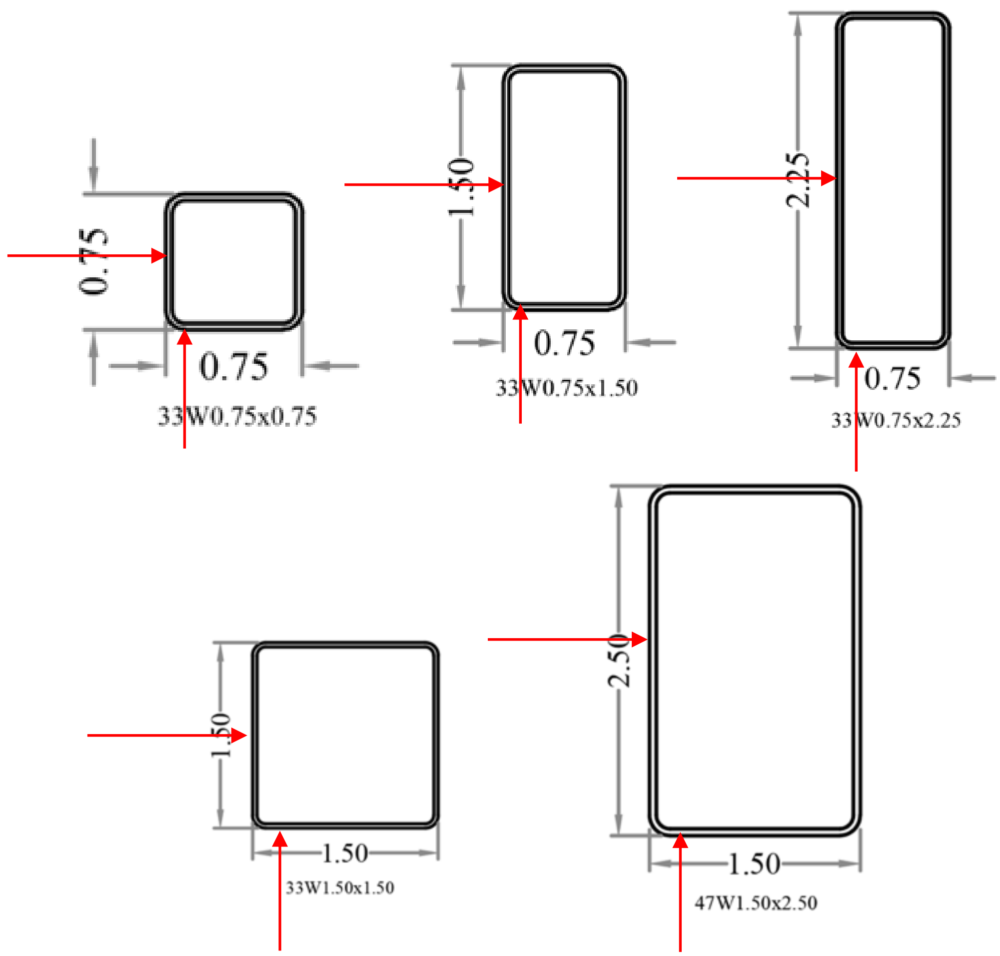



Figure 17: TrusSteel Web Coupon Location

Similarly, shown in Figure 17 are the web members. The members differ based on the dimensions of the web and the thickness of the metal. For these members, the horizontal arrow indicates the coupon taken from the center of the larger face. The vertical arrow indicated the coupon from the smaller face near the edge.

3.2.5 Test Matrix

| Test | Material | Location | Design Thickness (in) | True Thickness (in) | True Width (in) |
|---|---|---|---|---|---|
| 1B | 28TSC275 | Larger Face | .028 | .028 | 0.25 |
| 1S | 28TSC275 | Smaller Face | .028 | .028 | 0.25 |
| 2B | 43TSC275 | Larger Face | .043 | .044 | 0.25 |
| 2S | 43TSC275 | Smaller Face | .043 | .044 | 0.25 |
| 3B | 33TSC300 | Larger Face | .033 | .033 | 0.25 |
| 3S | 33TSC300 | Smaller Face | .033 | .033 | 0.25 |
| 4B | 54TSC300 | Larger Face | .054 | .054 | 0.25 |
| 4S | 54TSC300 | Smaller Face | .054 | .055 | 0.25 |
| 5B | 33W.75x.75 | Larger Face | .033 | .033 | 0.26 |
| 5S | 33W.75x.75 | Smaller Face | .033 | .033 | 0.25 |
| 6B | 33W.75x1.5 | Larger Face | .033 | .034 | 0.25 |
| 6S | 33W.75x1.5 | Smaller Face | .033 | .033 | 0.26 |
| 7B | 33W.75x2.25 | Larger Face | .033 | .033 | 0.25 |
| 7S | 33W.75x2.25 | Smaller Face | .033 | .033 | 0.25 |
| 8B | 33W1.5x1.5 | Larger Face | .033 | .033 | 0.25 |
| 8S | 33W1.5x1.5 | Smaller Face | .033 | .033 | 0.25 |
| 9B | 47W1.5x2.5 | Larger Face | .047 | .048 | 0.25 |
| 9S | 47W1.5x2.5 | Smaller Face | .047 | .048 | 0.25 |

Table 1: TrusSteel Material Test Matrix

Material tests were performed on each component of the truss at two different locations. The test matrix provided in Table 1 shows all locations that where tested. The coupon from the smaller face was near the corner and the coupon at the larger face was from the middle of the face.

## 3.3 Research Method Aiges

### 3.3.1 Truss Members

The trusses that are being tested consist of 14 members. There are 7 chord members and 7 web members that vary by size and thickness. Different chord and web members are used in different trusses that are being tested. USC and USD sections are chord members, while USWD and USW sections are web members. Shown in the following page are pictures showing the dimensions of chord and web members and how they differ from each other.

### 3.3.2 Test Location

Coupons will be created from two to three locations on each component of the truss. The first coupon will be from the center of the largest face, while the second and coupon will be near an edge of a smaller face. Red arrows in the diagrams below will indicate the location of the two coupons from each component.

3.3.3 Web Members

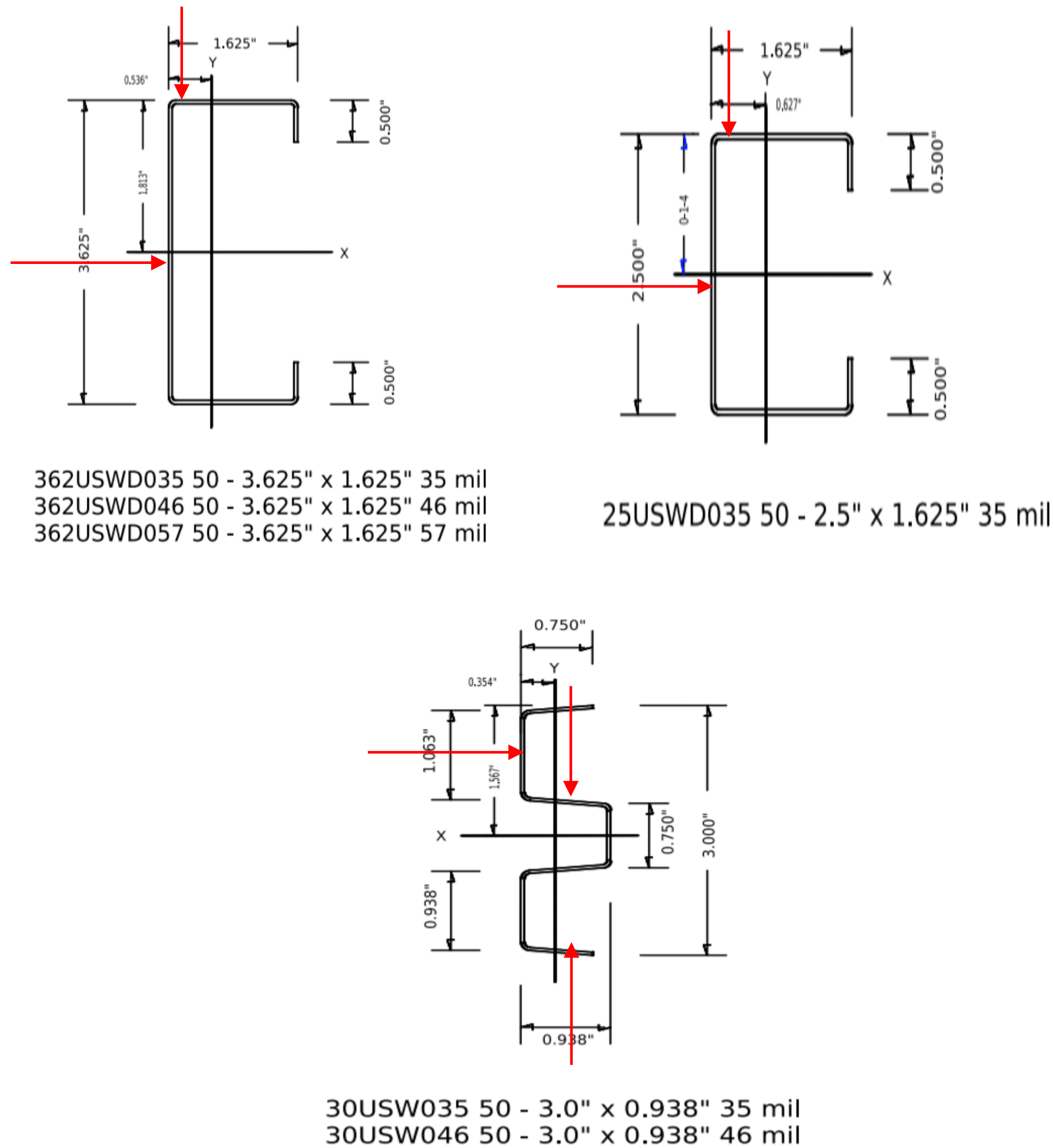



Figure 18: Aiges Web Coupon Locations

As seen in Figure 18, the USW & USWD members are web members that are differentiated by their heights and thicknesses in inches. The red arrows indicate the locations of each coupon. B members indicate the large face represented be the horizontal arrows. The vertical arrows represent the S (side) face. SI is the inner side face and SO is the outer side face.

## 3.3.4 Chord Members

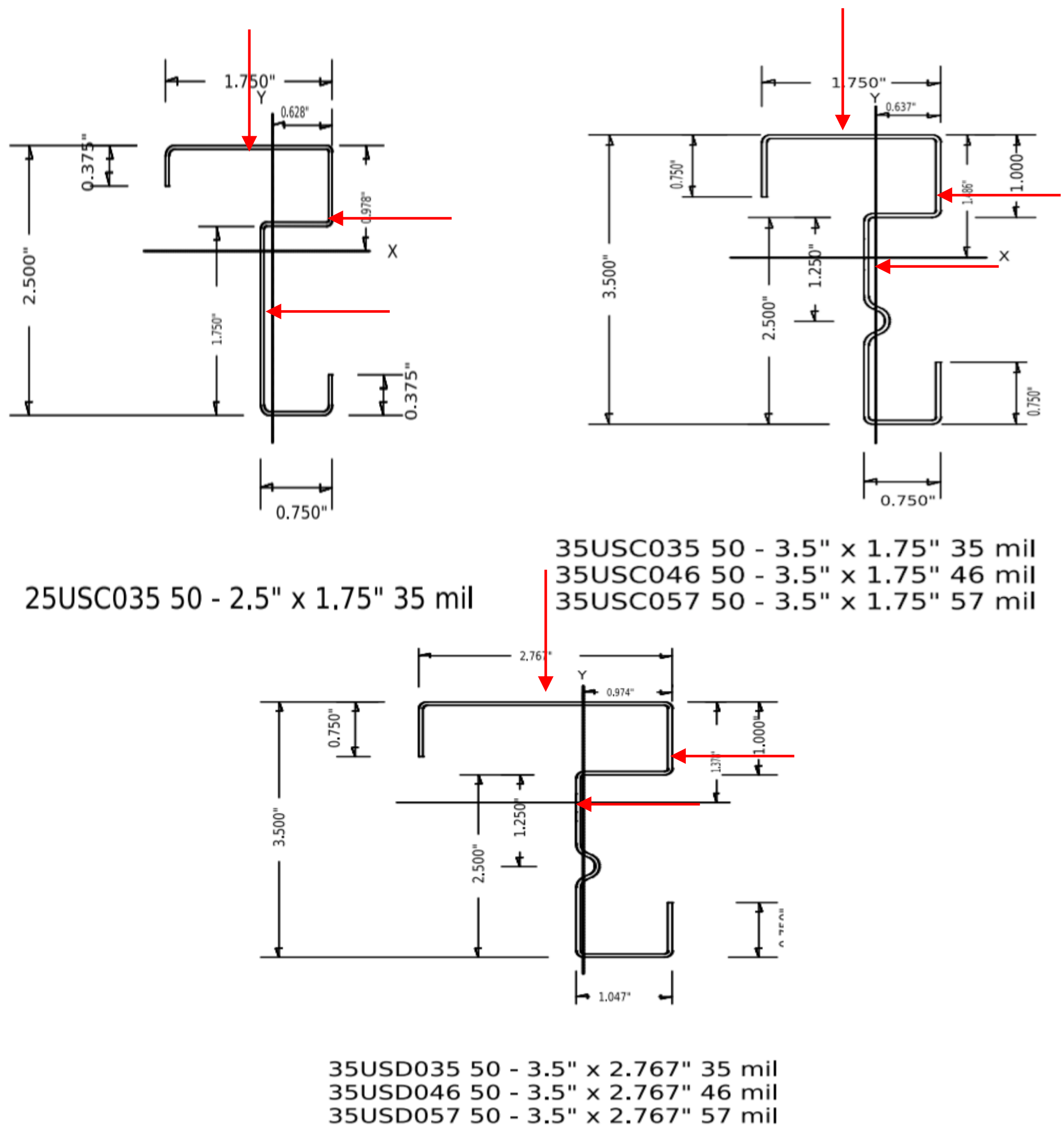



Figure 19: Aiges Chord Coupon Locations

Similarly, shown in Figure 19 are the chord members. The members differ based on the dimensions of the web and the thickness of the metal. For these members, the vertical arrow indicates the coupon taken from the center of the larger face (B member). The horizontal arrows indicated the coupon from the smaller face near the edge. The ST members are the top side members. The SB members are the bottom side members.

3.3.5 Test Matrix

| Test | Material | Location | Design Thickness (in) | True Thickness (in) |
|---|---|---|---|---|
| WD1-B | 362USWD35-B | Larger Face | .035 | .255 |
| WD1-S | 362USWD35-S | Smaller Face | .035 | .255 |
| WD2-B | 25USWD35-B | Larger Face | .035 | .255 |
| WD2-S | 25USWD35-S | Smaller Face | .035 | .255 |
| WD3-B | 362USWD46-B | Larger Face | .046 | .255 |
| WD3-S | 362USWD46-S | Smaller Face | .046 | .255 |
| WD4-B | 362USWD57-B | Larger Face | .057 | .255 |
| WD4-S | 362USWD57-S | Smaller Face | .057 | .255 |
| W1-B | 30USW35-B | Larger Face | .035 | .255 |
| W1-S | 30USW35-S | Smaller Face | .035 | .255 |
| W2-B | 30USW46-B | Larger Face | .046 | .255 |
| W2-S | 30USW46-S | Smaller Face | .046 | .255 |
| W3-B | 30USW57-B | Larger Face | .057 | .255 |
| W3-S | 30USW57-S | Smaller Face | .057 | .255 |
| C1-B | 35USC35-B | Larger Face | .035 | .255 |
| C1-S | 35USC35-S | Smaller Face | .035 | .255 |
| C2-B | 35USC57-B | Larger Face | .057 | .255 |
| C2-S | 35USC57-S | Smaller Face | .057 | .255 |
| C3-B | 35USC46-B | Larger Face | .046 | .255 |
| C3-S | 35USC46-S | Smaller Face | .046 | .255 |
| C4-B | 25USC35-B | Larger Face | .035 | .255 |
| C4-S | 25USC35-S | Smaller Face | .035 | .255 |
| D1-B | 35USD35-B | Larger Face | .035 | .255 |
| D1-S | 35USD35-S | Smaller Face | .035 | .255 |
| D2-B | 35USD57-B | Larger Face | .057 | .255 |
| D2-S | 35USD57-S | Smaller Face | .057 | .255 |
| D3-B | 35USD46-B | Larger Face | .046 | .255 |
| D3-S | 35USD46-S | Smaller Face | .046 | .255 |

Table 2: Aiges Material Test Matrix

Material tests were performed on each component of the truss at two to three different locations. The test matrix provided in Table 2 shows all locations that where tested. The coupon from the smaller face was near the corner and the coupon at the larger face was from the middle of the face.

## 3.4 Test Setup

3.4.1 Machine Description

The test is conducted on an Electromechanical Tensile Test Machine. This machine, when in operation, is stationary at the bottom and has a tensile force pulling at the top. The data from the machine readings show load, time, position and strain on the sample.

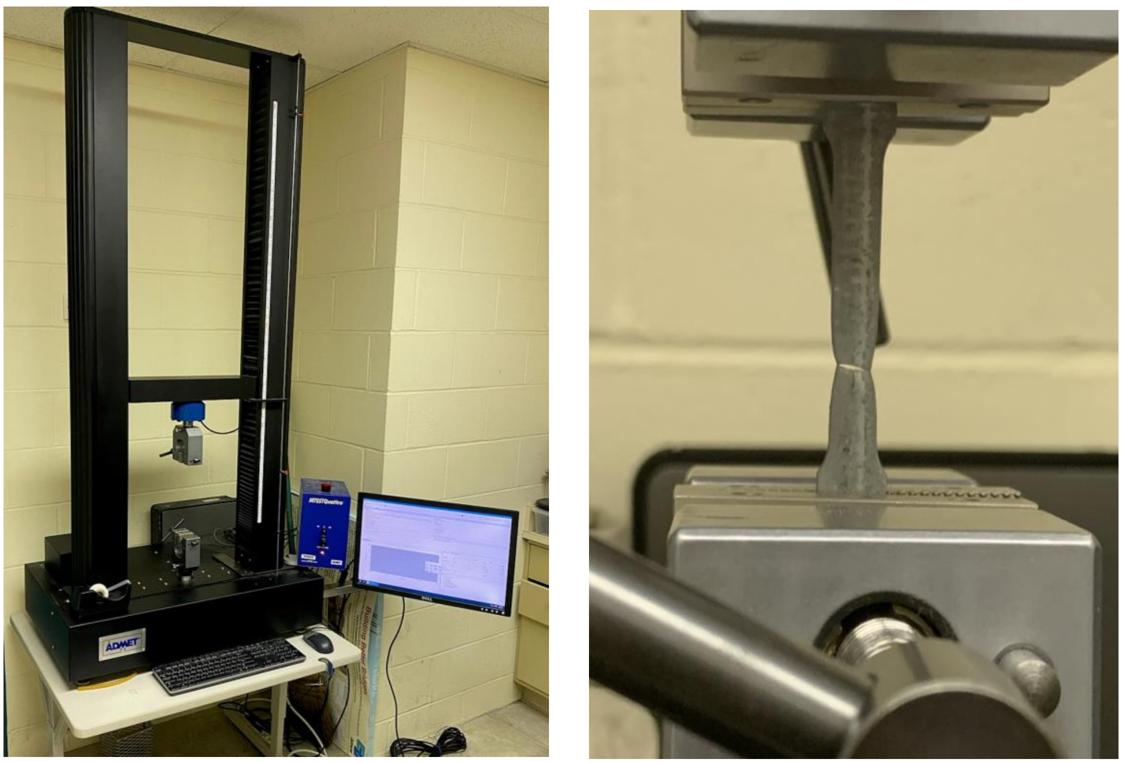
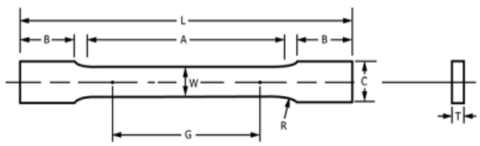


Figure 20: Electromechanical Tensile Test Machine

3.4.2 Specimen Information

For our test, we used an ASTM E8/E8M-16a Subsize Specimen (dimensions in inches) [2]. We created our sample using a waterjet machine to cut the coupon out of the face of the truss member. Locations where coupons were cut out of are shown in the research methods section.

E8/E8M – 16a$^{\epsilon 1}$




| Dimensions | | | |
|---|---|---|---|
| | Standard Specimens | | Subsize Specimen |
| | Plate-Type, 40 mm [1.500 in.] Wide | Sheet-Type, 12.5 mm [0.500 in.] Wide | 6 mm [0.250 in.] Wide |
| | mm [in.] | mm [in.] | mm [in.] |
| G—Gauge length (Note 1 and Note 2) | 200.0 ± 0.2 [8.00 ± 0.01] | 50.0 ± 0.1 [2.000 ± 0.005] | 25.0 ± 0.1 [1.000 ± 0.003] |
| W—Width (Note 3 and Note 4) | 40.0 ± 2.0 [1.500 ± 0.125, -0.250] | 12.5 ± 0.2 [0.500 ± 0.010] | 6.0 ± 0.1 [0.250 ± 0.005] |
| T—Thickness (Note 5) | | thickness of material | |
| R—Radius of fillet, min (Note 6) | 25 [1] | 12.5 [0.500] | 6 [0.250] |
| L—Overall length, min (Note 2, Note 7, and Note 8) | 450 [18] | 200 [8] | 100 [4] |
| A—Length of reduced parallel section, min | 225 [9] | 57 [2.25] | 32 [1.25] |
| B—Length of grip section, min (Note 9) | 75 [3] | 50 [2] | 30 [1.25] |
| C—Width of grip section, approximate (Note 4 and Note 9) | 50 [2] | 20 [0.750] | 10 [0.375] |

Figure 21: ASTM E8/E8M Coupon Dimensions [2]

Figure 22: Standard Water Jetted Coupon

<u>3.4.3 Setup Information</u>

To conduct the test, the specimen is inserted into the clamps on the Electromechanical Tensile Test Machine. The clamps were then tightened to ensure no slippage occurred during the test. The machine was set to a strain rate of -.1 in/min. The test was then begun and the machine provided a tensile force on the coupon. The machine plotted a load-strain curve that provides results on the material characteristics.

## 3.5 TrusSteel Results & Analysis

In the following tests, the results of a few key tests and an analysis of these results will be shown. Key information and comparisons will be made. See Appendix A for all results.

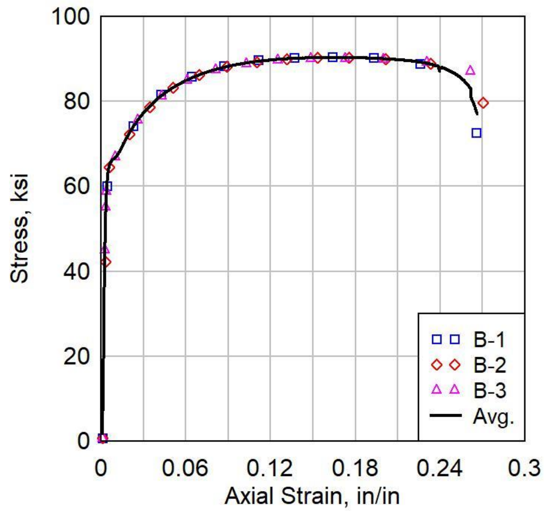



Figure 23: 28TSC275 Large Face

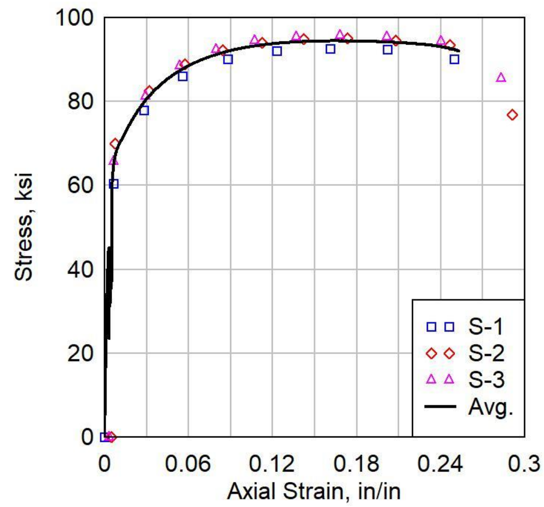



Figure 24: 28TSC275 Small Face

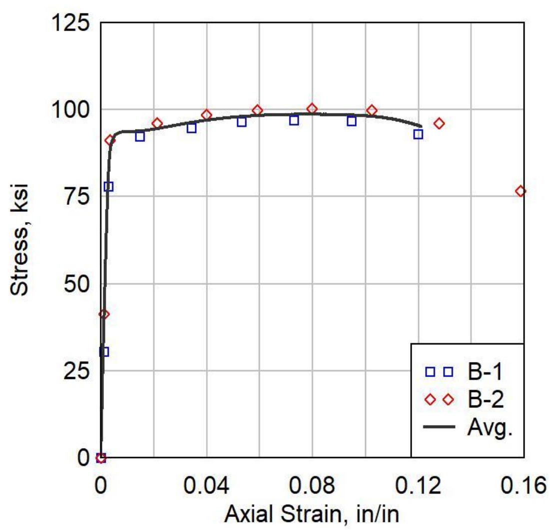



Figure 25: 43TSC275 Large Face

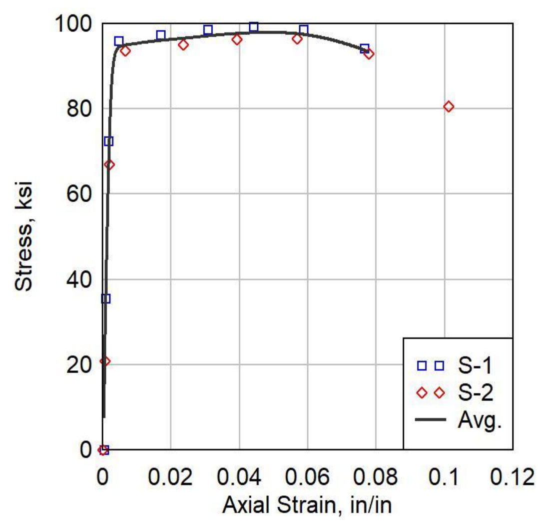



Figure 26: 43TSC275 Small Face

In the testing of the 28TSC275 and the 43TSC275 it was found that certain members have large differences in material properties. The 43TSC member had substantially less strain and a much higher yield stress. There was a slight change in the behavior of the material, especially post-peak for the 43TSC member. It also showed a higher modulus of elasticity. The 28TSC members behaved in a much more ductile fashion.

| Sample | Yield Stress (ksi) | Yield Strain | Modulus of Elasticity (ksi) | Ultimate Stress (ksi) | Strain at Ultimate | Maximum Strain |
|---|---|---|---|---|---|---|
| **28TSC275B** | 66 | 0.0026 | 25,546 | 90 | 0.166 | 0.266 |
| **28TSC275S** | 68 | 0.003 | 22,794 | 95 | 0.146 | 0.253 |
| **43TSC275B** | 92 | 0.0031 | 29,789 | 99 | 0.077 | 0.121 |
| **43TSC275S** | 93 | 0.0024 | 38,423 | 98 | 0.047 | 0.077 |
| **33TSC300B** | 74 | 0.0022 | 34,258 | 95 | 0.167 | 0.27 |
| **33TSC300S** | 72 | 0.0025 | 29,306 | 95 | 0.166 | 0.26 |
| **54TSC300B** | 65 | 0.0026 | 24,740 | 83 | 0.172 | 0.281 |
| **54TSC300S** | 72 | 0.0021 | 34,680 | 88 | 0.14 | 0.232 |
| **33W.75x.75B** | 69 | 0.0017 | 41,469 | 73 | 0.039 | 0.106 |
| **33W.75x.75S** | 67 | 0.0023 | 29,584 | 70 | 0.031 | 0.102 |
| **33W.75x1.5B** | 73 | 0.0022 | 33,323 | 78 | 0.049 | 0.117 |
| **33W.75x1.5S** | 70 | 0.0028 | 24,843 | 76 | 0.051 | 0.113 |
| **33W.75x2.25B** | 63 | 0.0025 | 25,023 | 73 | 0.104 | 0.221 |
| **33W.75x2.25S** | 63 | 0.0022 | 28,361 | 74 | 0.099 | 0.185 |
| **33W1.5x1.5B** | 60 | 0.0024 | 25,473 | 70 | 0.102 | 0.219 |
| **33W1.5x1.5S** | 61 | 0.0025 | 24,741 | 70 | 0.091 | 0.196 |
| **47W1.5x2.5B** | 72 | 0.0012 | 60,308 | 82 | 0.104 | 0.199 |
| **47W1.5x2.5S** | 74 | 0.0014 | 53,606 | 83 | 0.088 | 0.162 |

Table 3: TrusSteel Material Results

From analysis of test results, it is found that all members have yield stresses ranging from 60 to 93 ksi. The 43TSC275 members yielded at 92 and 93 ksi. If 43TSC275 members are removed from results, all members have a yield stress ranging between 60 to 74 ksi. Members have yield strains ranging from .0012 to .0031. The 47W1.5x2.5 have yield strain of .0012 and .0014. Excluding the 47W1.5x2.5 member, yield strains range from .00166 to .0031. Ultimate stress of members ranges from 70 to 99 ksi. Chord members have an ultimate stress range from 83 to 99 ksi. Web members have an ultimate stress range of 70 to 83 ksi. Strain at ultimate of members ranges from .031 to .17. Excluding

43TSC275 members, chord members strain at ultimate ranges from .14 to .17. Web members range from .031 to .104. Modulus of Elasticity of all members was in between 22,794 to 60,308. The 47W1.5x2.5 members had a modulus of elasticity that ranged in between 53,606 to 60,308. Excluding this member, the results were in a more consistent range of 22,794 to 41,469.

## 3.6 Aiges Results & Analysis

The following section shows two stress strain curves and the results of the material tests for the Aiges members. Appendix B shows all remaining stress strain curves.

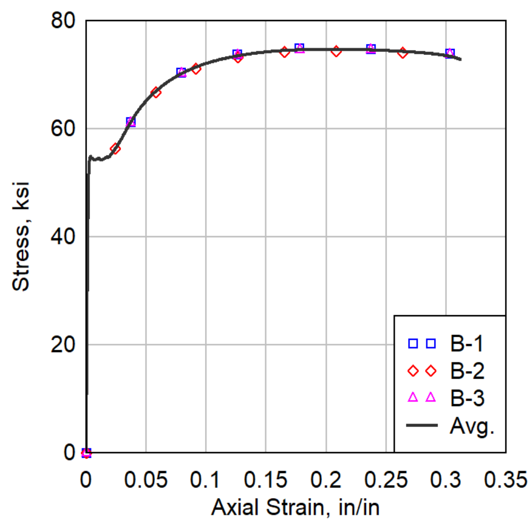



Figure 27: 362USWD35 Large Face

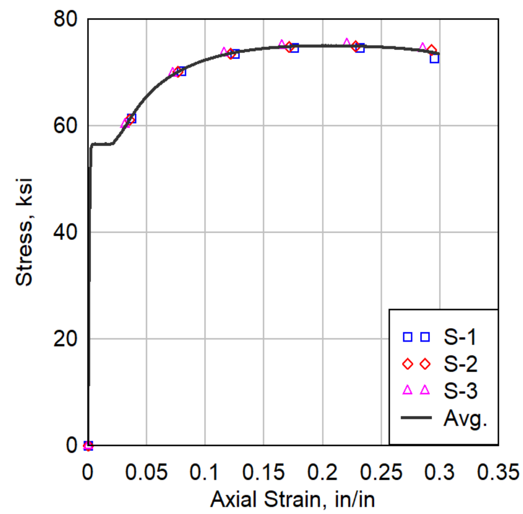



Figure 28: 362USWD35 Small Face

The previous two figures show the stress strain curve of the 362USWD35 member. In this test, the behavior of the member is similar despite the location the coupon was taken from. The material characteristics were also consistent with what is to be expected. No major difference was seen in Aiges as was seen with TrusSteel.

3.6.1 Results Table

| Sample | Yield Stress (ksi) | Yield Strain | Modulus of Elasticity (ksi) | Ultimate Stress (ksi) | Strain at Ultimate | Maximum Strain |
|---|---|---|---|---|---|---|
| 362USWD35-B | 55 | .0035 | 27,594 | 75 | .189 | .314 |
| 362USWD35-S | 57 | .0033 | 28,750 | 75 | .203 | .301 |
| 25USWD35-B | 59 | .0034 | 25,000 | 75 | .205 | .270 |
| 25USWD35-S | 59 | .0031 | 27,207 | 75 | .194 | .312 |
| 362USWD46-B | 60 | .0052 | 30,333 | 80 | .171 | .276 |
| 362USWD46-S | 60 | .0054 | 28,434 | 78 | .174 | .298 |
| 362USWD57-B | 61 | .0032 | 29,444 | 82 | .151 | .279 |
| 362USWD57-S | 61 | .0038 | 31,333 | 83 | .144 | .289 |
| 30USW35-B | 65 | .0034 | 30,000 | 85 | .120 | .187 |
| 30USW35-S | 62 | .0042 | 29,032 | 83 | .139 | .206 |
| 30USW46-B | 59 | .0023 | 29,508 | 76 | .176 | .303 |
| 30USW46-S | 59 | .0029 | 27,136 | 76 | .180 | .278 |
| 30USW57-B | 60 | .0056 | 28,647 | 81 | .159 | .255 |
| 30USW57-S | 62 | .0047 | 24,500 | 82 | .159 | .273 |
| 35USC35-B | 59 | .0046 | 27,429 | 79 | .148 | .243 |
| 35USC35-S | 60 | .0047 | 28,778 | 78 | .149 | .222 |
| 35USC57-B | 60 | .0040 | 26,949 | 80 | .164 | .284 |
| 35USC57-S | 58 | .0040 | 25,622 | 79 | .163 | .271 |
| 35USC46-B | 59 | .0048 | 31,630 | 77 | .174 | .311 |
| 35USC46-S | 61 | .0060 | 28,831 | 77 | .157 | .261 |
| 25USC35-B | 61 | .0049 | 27,059 | 82 | .139 | .236 |
| 25USC35-S | 62 | .0049 | 31,538 | 75 | .182 | .288 |
| 35USD35-B | 64 | .0049 | 29,068 | 86 | .127 | .195 |
| 35USD35-S | 63 | .0043 | 35,588 | 83 | .142 | .235 |
| 35USD57-B | 63 | .0038 | 27,842 | 83 | .144 | .245 |
| 35USD57-S | 62 | .0030 | 30,390 | 82 | .148 | .234 |
| 35USD46-B | 56 | .0057 | 22,069 | 74 | .195 | .321 |
| 35USD46-S | 57 | .0054 | 27,338 | 74 | .189 | .291 |

Table 4: Aiges Material Results

From analysis of test results, it is found that all members have yield stresses ranging from 55 to 65 ksi. Members have yield strains ranging from .0023 to .0060. Ultimate stress of members ranges from 74 to 86 ksi. Chord members have an ultimate stress range from 74 to 86 ksi. Web members have an ultimate stress range of 75 to 85 ksi. Strain at ultimate of members ranges from .120 to .205. Chord members strain at ultimate ranges from .127 to .195. Web members range from .120 to .205. Modulus of Elasticity of all members was in between 22,069 to 35,588.

## 3.7 Discussion and Summary

### 3.7.1 TrusSteel Discussion

The first important thing to note is that the use of the waterjet in the creation of our samples may have caused slight error in our results. As discussed in the literature review, the work done by Lehocka denotes the possibility that a 2.5-15% error may occur in the modulus of elasticity when waterjet is used. This may also explain a portion of some of the large variations in modulus of elasticity. Secondly, it was found that chord members had a higher ultimate stress then web members. Chord members also had a larger ultimate strain then web members. It was also found that the different locations that the coupon was cut out of from each member had a minimum impact on the stresses. However, the strain at yield did vary depending on the location of the coupon. This relates to the work of Abdel-Rahman and Sivakumaran found in the literature review. Our coupons were made from material near the corner, not at the corner, but our results exhibit similar stresses and ductility at both locations. Strain at yield, does however change, so we did see some difference in the performance. Lastly, it is important to note that imperfections in the material may cause slight variations between similar coupons.

3.7.2 Aiges Discussion

The Aiges chord and web members had a similar ultimate stress and ultimate strain. It is fair to conclude that chord and web members will behave the same under ultimate conditions. It was also found that the different locations that the coupon was cut out of from each member had a minimum impact on the stresses. Differences in stressed due to location were less than 5%. However, the strain at yield did vary depending on the location of the coupon. Strains at yield varied up to 25% depending on the location in the member that the coupon was cut out of. All these findings were consistent to the findings in the TrusSteel testing. One important observation made was that the yield stresses provided by Aiges are not accurate. The Aiges members are supposed to be composed of 50 ksi yield strength cold formed steel. This, however, is untrue, as seen by the yield stresses obtained in our testing. Yield stress ranged from 55 to 65 ksi, which means that there has been a change in material properties in the truss.

3.7.3 Summary

In conclusion, the material characteristics of every member composing TrusSteel and Aiges trusses were tested. It was found that material characteristics at different locations throughout the member have little impact on the material characteristics. It was also found that the yield stresses provided are not accurate. During the cold forming process, it is typical to cold roll the metal to achieve a required thickness. This cold rolling process, results in changes to material properties. It may cause the steel to yield and enter into plastic deformation. Member 43TSC275, as an example, seems to be well into plastic deformation. This will result in higher yield stress and lower strain when performing a uniaxial tension test of the material. This lower strain results in much less strain energy of the material, which results in a truss that does not behave in as ductile of a fashion under blast loads. This is an important issue that must be further studied when testing the blast resistance of cold formed steel trusses. Finally, results from these tests such as yield stress and strain, ultimate stress and strain and modulus of elasticity will be input into our numerical model simulation of the full-scale truss test to increase the accuracy of the results. This will allow for the most efficient design of a cold form steel roof truss under blast loads.

# 4 Aiges Connections

## 4.1 Preface

In this segment, the goal will be to test and characterize connections of cold form steel roof trusses. A test will be performed on every connection composition throughout the Aiges full scale truss. The connections throughout the truss differ by member type, amount of screws and screw spacing. A tension test using a MTS-Hydraulic Tensile Test Machine will be performed on the connections. To obtain our connection data, the tensile test must be performed on a web member and a galvanized steel filler plate that represents the chord member. A connection test between the chord and web member is unfeasible, so a substitution filler plate with similar characteristics will provide the most accurate connection characteristics. The testing will provide the stiffness, deflection, load capacity and other connection properties. These properties will be input into the full scale numerical model. The tests will also give insights on types of failure that occur in different connections and the causes of the failures.

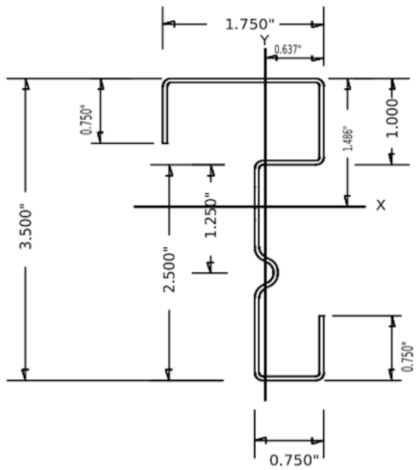
## 4.2 Research Method

### 4.2.1 Background

This section discusses the different materials that are used in both the actual trusses and in the connection test. The truss members are made from cold formed steel and are held together by self-tapping screws. The substitution plate for the connection test will be made of galvanized steel with similar thickness as the chord members. The trusses that are being tested consist of 14 members. There are 7 chord members and 7 web members that vary by size and thickness. Different chord and web members are used in different trusses that are being tested. USC and USD sections are chord members, while USW and

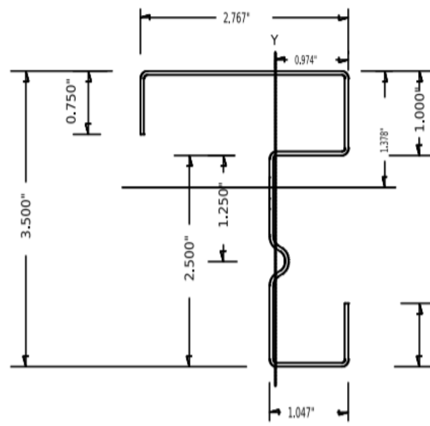
USWD sections are web members. Shown in the figures below are the dimensions of chord and web members and how they differ from each other.

4.2.2 Chord Members



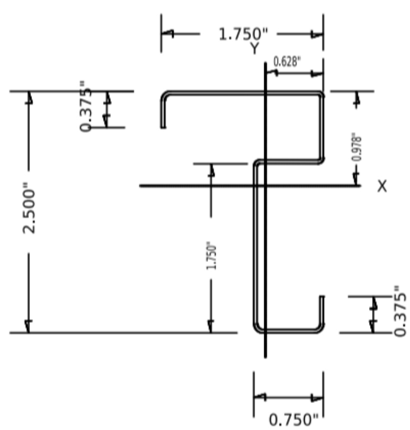

35USC035 50 - 3.5" x 1.75" 35 mil 50 ksi
35USC046 50 - 3.5" x 1.75" 46 mil 50 ksi
35USC057 50 - 3.5" x 1.75" 57 mil 50 ksi

Figure 29: 35USC Chord Members




35USD035 50 - 3.5" x 2.767" 35 mil 50 ksi
35USD046 50 - 3.5" x 2.767" 46 mil 50 ksi
35USD057 50 - 3.5" x 2.767" 57 mil 50 ksi

Figure 30: 35USD Chord Members




25USC035 50 - 2.5" x 1.75" 35 mil 50 ksi

Figure 31: 25USC Chord Member

As seen above, the USC and USD members are chord members that are differentiated by their heights and thicknesses in inches.

4.2.3 Web Members

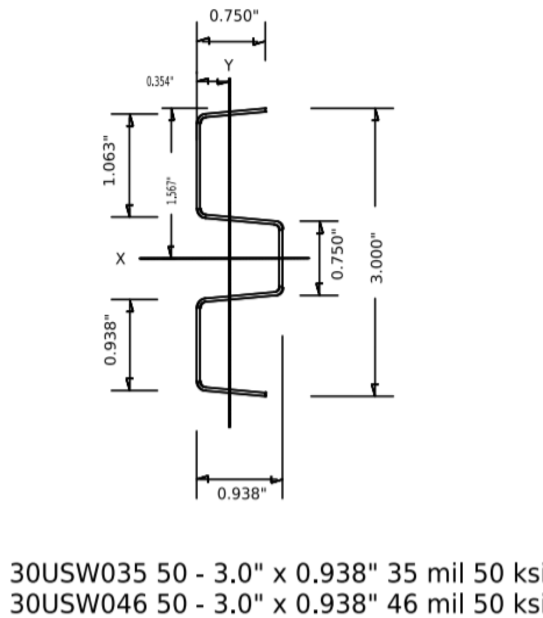



Figure 32: 30USW Web Members

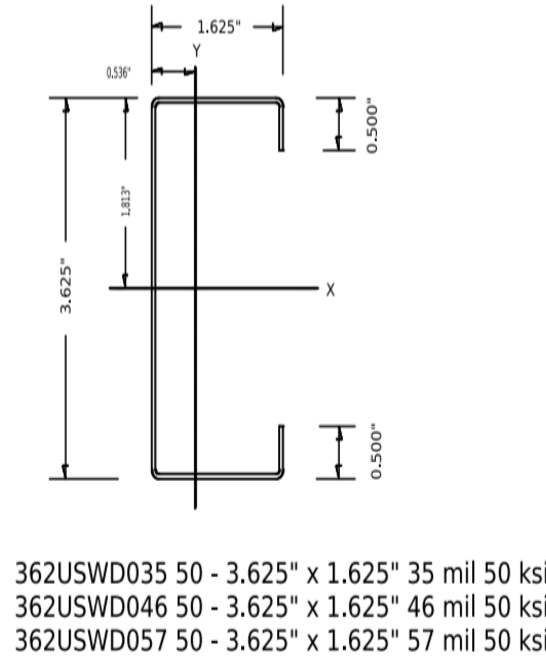



Figure 33: 362USWD Web Members

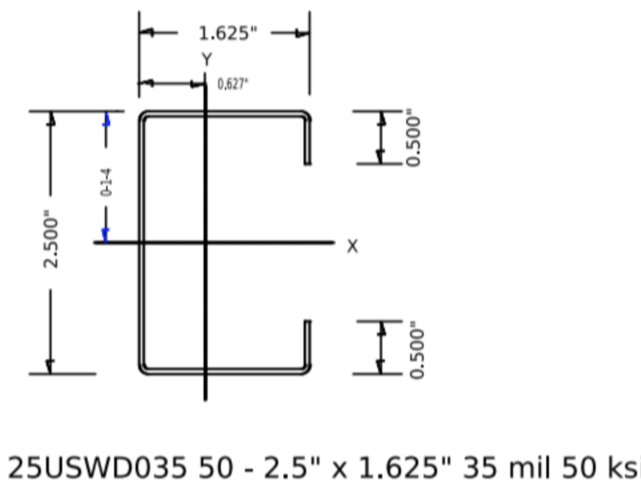



Figure 34: 25USWD Web Member

Shown above are the USW and USWD web members. A 7th member, 30USW057, is also a part of our truss. It has the same dimensions as the other 30USW members, but differs in thickness. It has a thickness of .057 inches.

4.2.4 Connection Matrix

Connections throughout the trusses differ due to members composing the connection, amount of screws and location of the screws. To perform tests, substitution plates must be created in place of chord members. The plates are composed of galvanized steel that is of similar thickness to the chord members. A diagram of the steel substitution plate will be shown in Figure 35. To obtain accurate results, all possible connections in the truss must be tested. Table 5 and Table 6 are the test matrixes for all member compositions and screw amounts.

4.2.5 Chord Substitution Plate

Chord Element Substitution plates were created in .035, .046 and .057 inch thicknesses. These plates where screwed onto the web member pulled apart by the tensile test. Further descriptions and diagrams can be found in Test Setup.

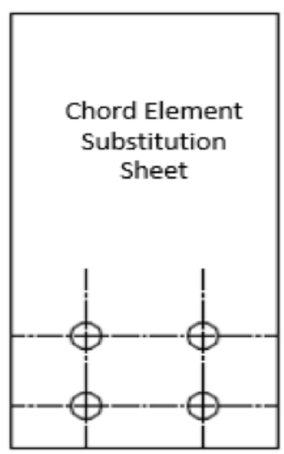



Figure 35: Chord Element Substitution Plate

4.2.6 Connection Matrix

The following test matrix shows each type of connection's chord member, web member, substitution plate used and number of screws. This matrix accounts for all connections in the truss composition.

<table>
<tr><th colspan="2">Chord</th><th>Web</th><th rowspan="2"># of Screws</th><th rowspan="2">Notation of Samples</th></tr>
<tr><th>Section</th><th>Sheet Gauge of the substituted plate (inch)</th><th>Section</th></tr>
<tr><td rowspan="6">C1:35USC35<br>C4:25USC35</td><td rowspan="9">0.035</td><td rowspan="6">W1:30USW35</td><td>2</td><td>035-30USW35-2</td></tr>
<tr><td>3</td><td>035-30USW35-3</td></tr>
<tr><td>4</td><td>035-30USW35-4</td></tr>
<tr><td>6</td><td>035-30USW35-6</td></tr>
<tr><td>7</td><td>035-30USW35-7</td></tr>
<tr><td>8</td><td>035-30USW35-8</td></tr>
<tr><td>C1:35USC35</td><td>W2:30USW46</td><td>10</td><td>035-30USW46-10</td></tr>
<tr><td>C1:35USC35</td><td>W3:30USW57</td><td>7</td><td>035-30USW57-7</td></tr>
<tr><td>C4:25USC35</td><td>W3:30USW57</td><td>8</td><td>035-30USW57-8</td></tr>
<tr><td rowspan="5">C2:35USC57</td><td rowspan="11">0.057</td><td rowspan="5">W1:30USW35</td><td>2</td><td>057-30USW35-2</td></tr>
<tr><td>3</td><td>057-30USW35-3</td></tr>
<tr><td>6</td><td>057-30USW35-6</td></tr>
<tr><td>10</td><td>057-30USW35-10</td></tr>
<tr><td>12</td><td>057-30USW35-12</td></tr>
<tr><td rowspan="6">C2:35USC57</td><td rowspan="6">W2:30USW46</td><td>2</td><td>057-30USW46-2</td></tr>
<tr><td>3</td><td>057-30USW46-3</td></tr>
<tr><td>6</td><td>057-30USW46-6</td></tr>
<tr><td>7</td><td>057-30USW46-7</td></tr>
<tr><td>8</td><td>057-30USW46-8</td></tr>
<tr><td>11</td><td>057-30USW46-11<br>Trial 1,2</td></tr>
<tr><td rowspan="4">C3:35USC46</td><td rowspan="6">0.046</td><td rowspan="4">W1:30USW35</td><td>2</td><td>046-30USW35-2</td></tr>
<tr><td>3</td><td>046-30USW35-3</td></tr>
<tr><td>6</td><td>046-30USW35-6</td></tr>
<tr><td>10</td><td>046-30USW35-10</td></tr>
<tr><td rowspan="2">C3:35USC46</td><td rowspan="2">W2:30USW46</td><td>7</td><td>046-30USW46-7</td></tr>
<tr><td>11</td><td>046-30USW46-11<br>Trial 1,2</td></tr>
</table>

Table 5: Aiges USC Test Matrix

| Chord | | Web | # of Screws | Notation of Samples |
|---|---|---|---|---|
| Section | Sheet Gauge of the substituted plate (inch) | Section | | |
| D1:35USD35 | 0.035 | WD1:362USWD35 | 7 | 035-362USWD35-7 |
| | | | 8 | 035-362USWD35-8 |
| | | | 9 | 035-362USWD35-9 |
| | | | 16 | 035-362USWD35-16 |
| | | WD2:25USWD35 | 2 | 035-25USWD35-2 |
| | | | 3 | 035-25USWD35-3 |
| | | | 5 | 035-25USWD35-5 |
| | | | 7 | 035-25USWD35-7 |
| | | | 11 | 035-25USWD35-11 |
| | | WD3:362USWD46 | 8 | 035-362USWD46-8 |
| | | | 12 | 035-362USWD46-12 |
| | | WD4:362USWD57 | 11 | 035-362USWD57-11 |
| D2:35USD57 | 0.057 | WD1:362USWD35 | 15 | 057-362USWD35-15 |
| | | | 18 | 057-362USWD35-18 |
| | | WD2:25USWD35 | 2 | 057-25USWD35-2 |
| | | | 3 | 057-25USWD35-3 |
| | | | 7 | 057-25USWD35-7 |
| | | | 8 | 057-25USWD35-8 |
| | | WD3:362USWD46 | 10 | 057-362USWD46-10 |
| | | WD4:362USWD57 | 7 | 057-362USWD57-7 |
| | | | 9 | 057-362USWD57-9 |
| D3:35USD46 | 0.046 | WD1:362USWD35 | 18 | 046-362USWD35-18 |
| | | WD2:25USWD35 | 2 | 046-25USWD35-2 |
| | | | 3 | 046-25USWD35-3 |
| | | | 8 | 046-25USWD35-8 |
| | | WD3:362USWD46 | 10 | 046-362USWD46-10 |
| | | WD4:362USWD57 | 10 | 046-362USWD57-10 |
| | | | Total | 52 |

Table 6: Aiges USD Test Matrix

## 4.3 Test Setup

4.3.1 Machine Description

The test is conducted on an MTS- Hydraulic Tensile Test Machine. This machine, when in operation, is stationary at the top and has a tensile force pulling at the bottom. The data from the machine readings shows load and deflection of the connection.

4.3.2 Setup Information

In our test setup, the desired web member is attached to the desired substitution sheet using self-tapping screws. The screw locations varied depending on the amount of screws, but usually they were placed an inch below the top of the substitution plate. The connection is then attached to the two grip plates with bolts. Filler plates are used to match up the thicknesses of the different types of connections so that there is no eccentricity. The gripping plates are then attached to the MTS – Hydraulic Tensile Test Machine. The test is performed at a strain rate of .1 in/min.

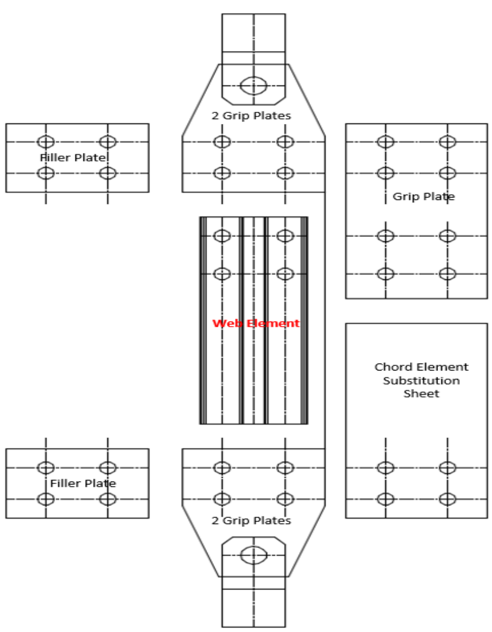



Figure 36: Test Setup 2D

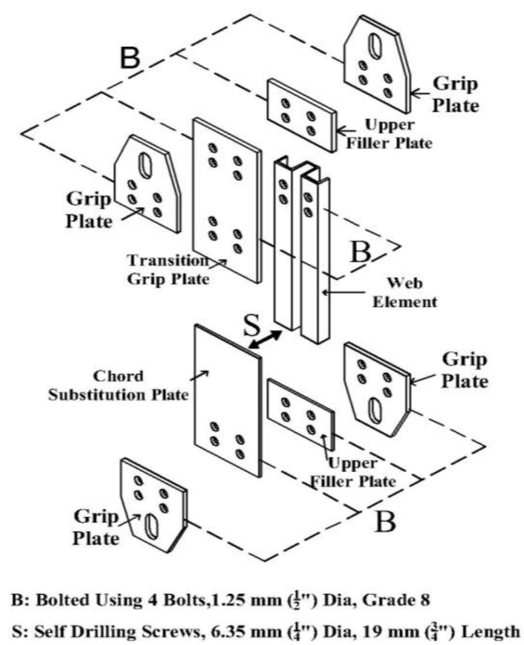



Figure 37: Test Setup 3D


Figure 38: Aiges Connection Test Setup Pictures

Figure 36 & 37 show a 2D and 3D test setup diagram. Figure 38 shows pictures taken of the test setup with both types of connections. A connection using a USWD web is the same as a USW web, just the member is changed. Filler plates at the bolts must also be changed depending on web member and substitution plate thicknesses. The substitution plate is pulled down in tension by the MTS machine which allows for a quasi-static tension test on the connection.

4.3.3 Substitution Plate Characteristics

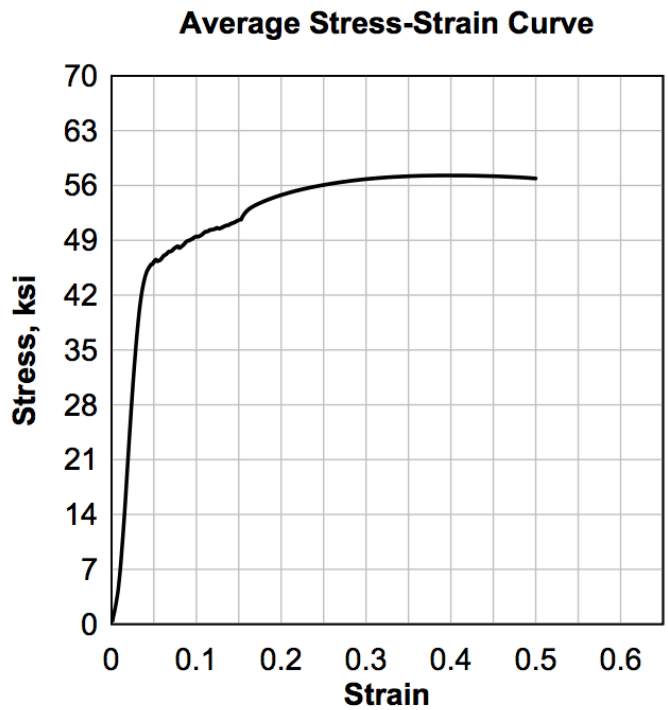


Figure 39: Average Stress Strain Curve

| Characteristic | Value |
|---|---|
| Mean Yield Stress | 45 ksi |
| Mean Yield Strain | 0.04 |
| Mean Ultimate Stress | 57 ksi |
| Mean Ultimate Strain | 0.4 |

Table 7: Substitution Plate Characteristics

The substitution plates used had equal thicknesses as the chord member they represented. The mean yield and ultimate stress of the substitution plate where 45 ksi and 57 ksi, respectively. The mean yield and ultimate strain where .04 and .4, respectively.

## 4.4 Aiges Results & Analysis

In the following section, results of Aiges connections will be displayed and a brief analysis of trends and performance of the connection will be performed. Remaining Aiges connection results will be found in Appendix C.

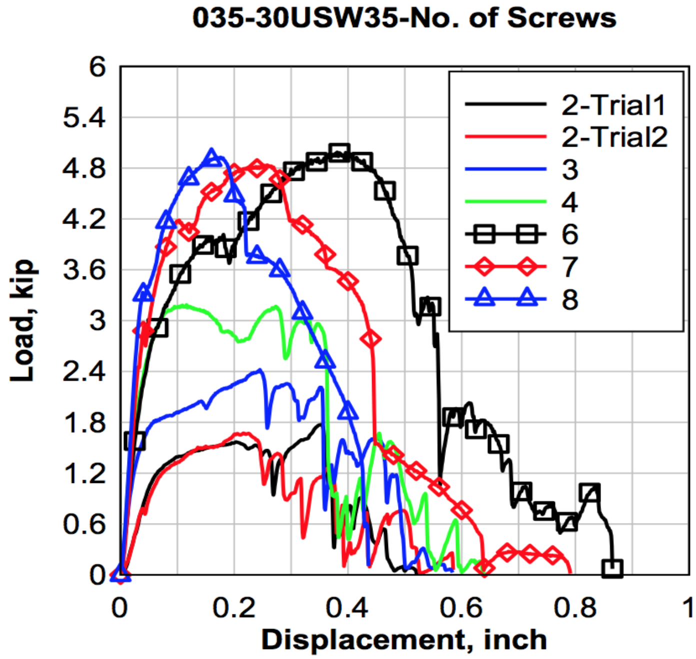



Figure 40: 035-30USW35 Results

| Sample | Stiffness (kip/in) | Strain Energy (kip-in) |
|---|---|---|
| 035-30USW35-2 | 21.84 | 0.56 |
| 035-30USW35-3 | 36.42 | 0.88 |
| 035-30USW35-4 | 50.44 | 1.20 |
| 035-30USW35-6 | 50.06 | 2.53 |
| 035-30USW35-7 | 87.35 | 1.95 |
| 035-30USW35-8 | 98.52 | 1.47 |

Table 8: 035-30USW35 Stiffness

The first important thing to note is that, in general, the capacity of the connection rises with increased amount of screws. As seen in Figure 40, for example, the peak loads of the connections are approximately: 1.5 kip with 2 screws, 2.4 kip with 3 screws, 3 kip with 4 screws and 4.8 kip with 6-8 screws. There are other factors that will be discussed later that cause the load to level off at 6 screws, but the trend is clear that the load capacity of the connection will go up if the amount of screws increases. The second important observation is that the displacement of the connection may decrease if the number of screws increases. As seen in Figure 40, the displacement of the 6 screw connection is larger than that of the 7 screw connection. The 7 screw connection has a larger displacement than the 8 screw connection. When combining these two findings, it is confirmed that increasing the number of screws will increase the stiffness, which is the load over the displacement of the connection. This trend is shown in all of our testing. Table 8, among others, shows the increase in stiffness relative to number of screws. The stiffness (kip/in) increases from 21.84 for the 2 screw connection all the way up to 98.52 for the 8 screw connection. Strain energy of the connection loosely increases with number of screws, but can level off or decrease when other factors such as screw concentration or failure type effect the loose trend. As seen in Table 8, the strain energy increases until 6 screws, but when using more screws very closely spaced together, the strain energy begins to decrease.

Provided in Table 9 and Table 10 below are the stiffness and load for all USW and USWD connections tested for the Aiges trusses, respectively.

| Notation of Samples | Stiffness (kip/in) | Load (kip) | Strain Energy (kip-in) |
|---|---|---|---|
| 035-30USW35-2 | 21.84 | 1.5 | 0.56 |
| 035-30USW35-3 | 36.42 | 2.4 | 0.88 |
| 035-30USW35-4 | 50.44 | 3.2 | 1.20 |
| 035-30USW35-6 | 50.06 | 4.9 | 2.53 |
| 035-30USW35-7 | 87.35 | 4.8 | 1.95 |
| 035-30USW35-8 | 98.52 | 4.9 | 1.47 |
| 035-30USW46-10 | 54.95 | 5.6 | 2.99 |
| 035-30USW57-7 | 105.51 | 5.2 | 2.05 |
| 035-30USW57-8 | 119.75 | 6.7 | 2.16 |
| 057-30USW35-2 | 62.77 | 2.4 | 0.79 |
| 057-30USW35-3 | 39.57 | 3.4 | 1.30 |
| 057-30USW35-6 | 95.11 | 6.7 | 2.52 |
| 057-30USW35-10 | 76.30 | 6.7 | 3.20 |
| 057-30USW35-12 | 82.76 | 7.2 | 2.35 |
| 057-30USW46-2 | 39.54 | 2.8 | 0.73 |
| 057-30USW46-3 | 41.02 | 4.8 | 1.31 |
| 057-30USW46-6 | 82.62 | 6.9 | 2.53 |
| 057-30USW46-7 | 85.29 | 7.3 | 3.52 |
| 057-30USW46-8 | 108.43 | 8.0 | 3.42 |
| 057-30USW46-11 Trial 1,2 | 124.35; 108.35 | 8.7; 9.0 | 2.57; 3.58 |
| 046-30USW35-2 | 27.09 | 1.8 | 0.72 |
| 046-30USW35-3 | 27.53 | 2.7 | 1.08 |
| 046-30USW35-6 | 47.30 | 4.9 | 2.15 |
| 046-30USW35-10 | 82.64 | 6.3 | 2.31 |
| 046-30USW46-7 | 76.01 | 6.5 | 3.09 |
| 046-30USW46-11 Trial 1,2 | 83.49; 116.60 | 7.7; 8.5 | 4.64; 3.96 |

Table 9: Aiges USW Results

| Notation of Samples | Stiffness (kip/in) | Load (kip) | Strain Energy (kip-in) |
|---|---|---|---|
| 035-362USWD35-7 | 53.25 | 5.1 | 2.54 |
| 035-362USWD35-8 | 103.05 | 5.5 | 2.16 |
| 035-362USWD35-9 | 105.34 | 5.6 | 2.55 |
| 035-362USWD35-16 | 109.47 | 6.5 | 2.47 |
| 035-25USWD35-2 | 35.07 | 1.5 | 0.45 |
| 035-25USWD35-3 | 42.26 | 2.2 | 0.69 |
| 035-25USWD35-5 | 84.85 | 3.6 | 1.42 |
| 035-25USWD35-7 | 95.03 | 4.6 | 1.39 |
| 035-25USWD35-11 | 113.24 | 5.9 | 2.06 |
| 035-362USWD46-8 | 78.09 | 5.8 | 2.12 |
| 057-25USWD35-2 | 31.71 | 2.1 | 0.68 |
| 057-25USWD35-3 | 35.05 | 3.0 | 0.83 |
| 057-25USWD35-7 | 83.75 | 5.3 | 1.91 |
| 057-25USWD35-8 | 87.62 | 6.0 | 2.51 |
| 057-362USWD57-7 | 49.35 | 8.4 | 2.88 |
| 057-362USWD57-9 | 150.84 | 10.1 | 3.88 |
| 046-25USWD35-2 | 37.076 | 1.8 | 0.63 |
| 046-25USWD35-3 | 51.221 | 2.5 | 0.81 |
| 046-25USWD35-8 | 113.764 | 6.5 | 3.33 |

Table 10: Aiges USWD Results

The general trend of load and stiffness increasing with number of screws and increased member thicknesses can be seen in the overall results shown in the tables above. Strain energy also loosely increases with number of screws.

## 4.5 Discussion and Summary

4.5.1 Discussion

For USW members, there are 6 different member combinations of connections in the truss. These member combinations also had varying amounts of screws. As to be expected, increasing the amount of screws in the connection increases the load capacity and, in certain cases, decreases the displacement. In general, connection stiffness also increases when increasing the number of screws. There are a few cases where stiffness does not increase when increasing the number of screws. This is believed to be due to the screw spacing being decreased. When the connection has an adequate screw spacing, adding screws increases the load capacity and decreases the displacement, therefore increasing the stiffness.

Types of failure varied with the number of screws in the connection and the thickness of the two members composing the connections. When less screws were used in the connection, typically 2-4 screws, pull out failures would occur. When increasing up to 5-6 screws, failures have bearing deformation and tearing also occur. With a medium number of screws (5-6) there seemed to be a combined failure. For example, in one sample, half of the screws may experience pull out failure, while the other side may experience tearing of the plate failure. In this medium range of screws, either pull out of screws or tearing of thinnest member failure could occur, depending on the thickness of the components of the connection. When adding more screws, 7-8+, tearing of the plate was the main source of failure. When tear failure occurred, it typically occurred in the thinner component. When increasing the thickness of the components, load capacity of the connection increases due to increased strength of the plate and member. In tests where we had large numbers of screws that were spaced out to prevent stress concentration, failure in the member occurred in the gripping plate between the bolt holes of the thinnest member.

One potential problem that may occur when it comes to increases in capacity and stiffness relative to number of screws is screw concentration. Screw concentration, also known as the group effect, is when screws are placed extremely close to each other, resulting in non-proportional behavior of load and stiffness to amount of screws. The group effects mentioned by Laboube & Sokol [10], and Fairuz & Hieng Ho [11], in the literature review (reference 2.3) are seen in our testing. Figure 41 shows the screw location in the connection. As seen in the 10 screw connection, the screws are so close together that it causes a group effect that results in the connection not being at a capacity proportional to the number of screws added.

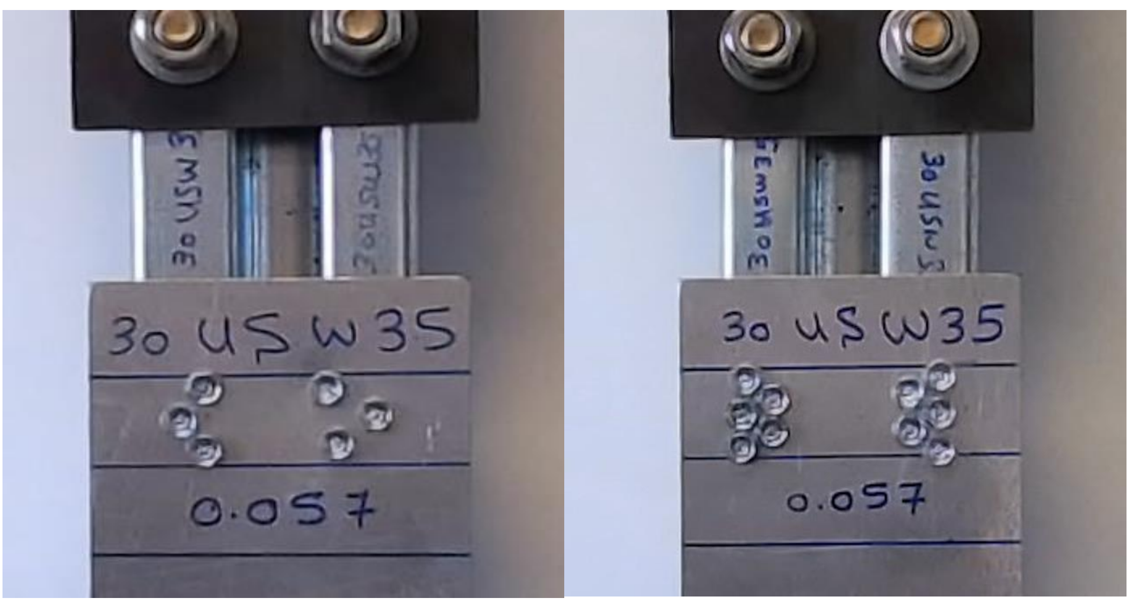



Figure 41: 057-30USW35-6/10 Screw Concentration

The failure type of the connection is dependent on number of screws, screw spacing and components composing the connection. The first failure often seen was pull-out of the screw failure. Pull-out of the screw failure typically happened in connections with 2-4 screws. It was also often accompanied by tilting failure. Sivapathasundaram & Mahendran [14], and Liu, Liu, and Feng [15] had similar results regarding findings of pull-out and tilting failure. Figure 42 shows a pull-out of the screw failure in our connection and Figure 42 shows an example of tilting failure. Typically these happen in conjuction with each other.


Figure 42: Pull-out Failure

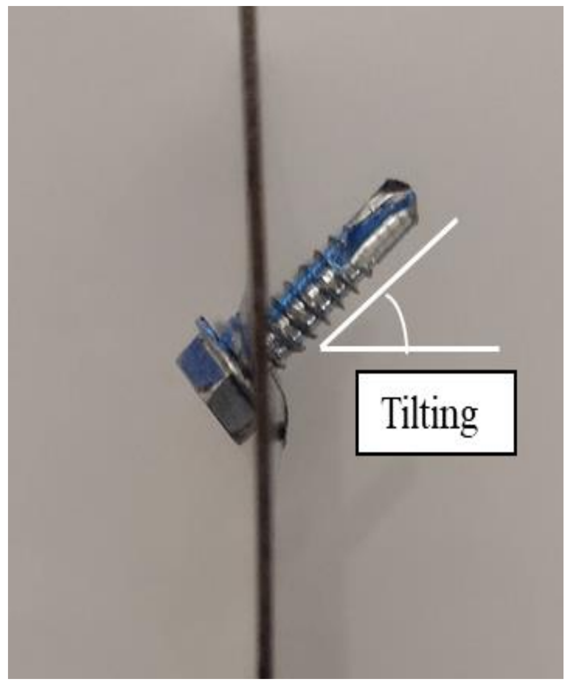



Figure 43: Tilting of Screw

The second failure often seen was the combination of a pull-out failure and a bearing & tearing failure. This failure also exhibited a tilting tendency of the screws. This combination failure was typically seen between 5-6 screws. As seen in Figure 44, half of the connection failed due to pull-out and some bearing, while the other half of the connection shows tearing. The connection also has tilting of the screws.


Figure 44: Combined Failure

Third, when increasing number of screws to 7-8 or more, bearing and tearing failure was typically experienced. This failure would result in the screws staying inside of the connection and the material itself failing. Initially, a bearing deformation begins followed by a complete tearing of the material. This failure most closely relates to the failures found by Yan, Mu, Xie and Yu [18] where bearing failure occurs followed by the tearing of the material. Tilting tendency was also exhibited in this failure type. Figure 45 shows bearing and tearing failure in our connection testing.

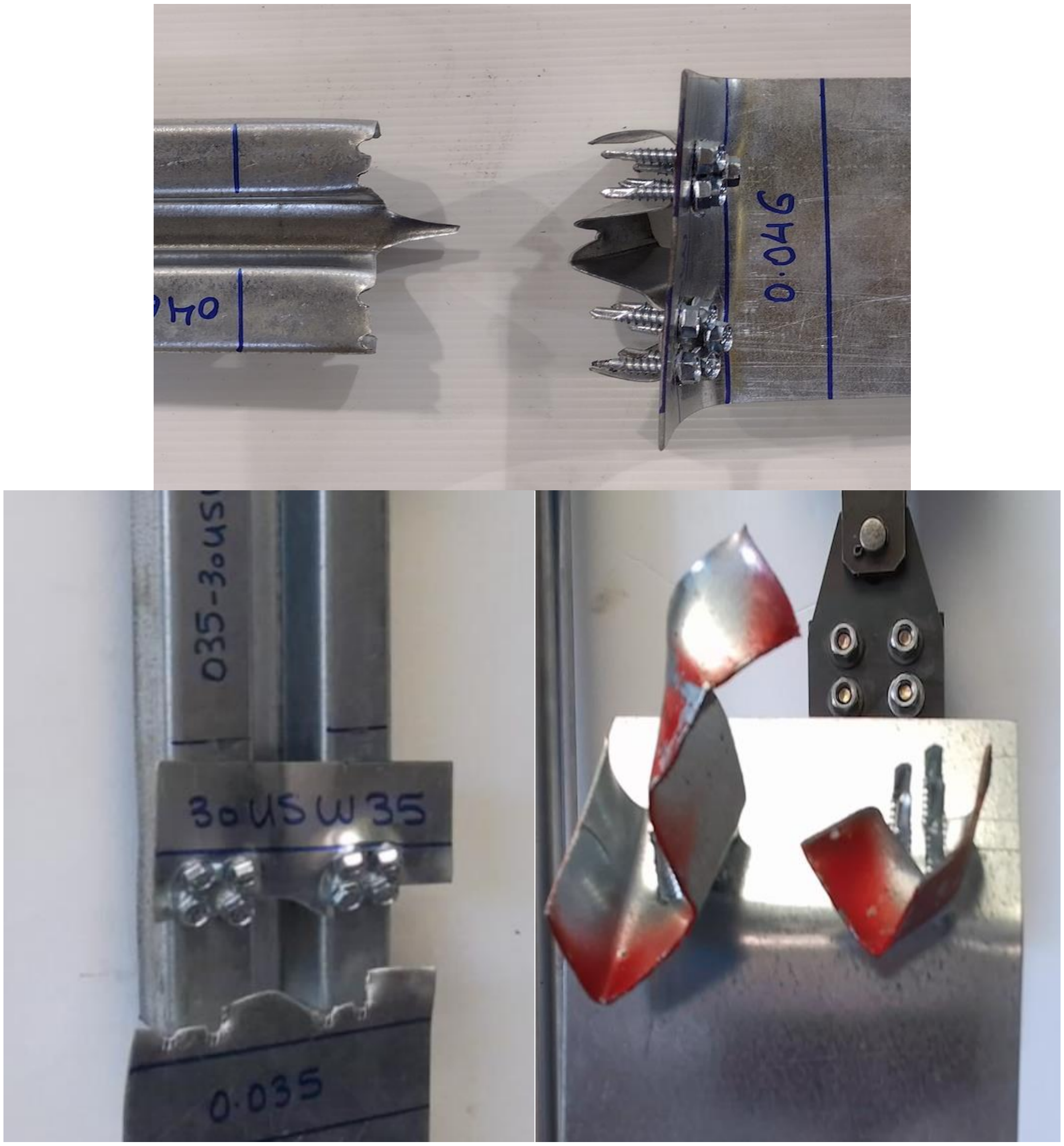



Figure 45: Bearing and Tearing Failure

Lastly, connections with large amounts of screws with large amounts of spacing experienced a unique type of failure. The failure would occur at the bolt holes far away from the connection as seen in Figure 46. This all but confirms that screw spacing has a massive impact on the strength of the connection. The elimination of screw concentration (group effect) allows the connection to perform much better and barely exhibit any signs of failure when the material failed at the bolt holes.


Figure 46: Bolt Hole Failure

<u>4.5.2 Summary</u>

In conclusion, the results of the conducted tests will help greatly improve the accuracy of the numerical model for full-scale truss testing. Connection characteristics such as load capacity, displacement and stiffness will be applied to the numerical model to enhance the results, and improve the performance of the trusses. It was found that, under normal circumstances, increasing number of screws increases load capacity, decreases displacement, hence increasing stiffness. A study of failure types such as screw pull-out, tilting, bearing and tearing on our connection was also performed. This study provided data on different failure types that will occur depending on different variables such as amount of screws used. Figure 47 gives a visual summary of how a typical connection may fail.

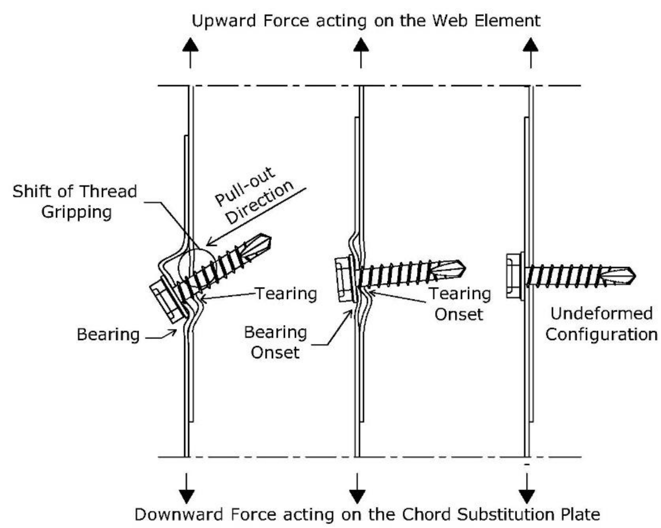



Figure 47: Typical Connection Failure

The testing also provided vital knowledge in regard to screw spacing. It was found that decreased screw spacing caused concentration that resulted in the capacity of the connection not increasing proportionally to the number of screws. When adequate screw spacing was used, the connection performed at a much higher level. In the testing on the full-scale trusses done by Treece [1], he notes that screw spacing is an issue causing unsatisfactory performance for connections that require higher capacities. This leads to the recommendation that screw spacing be increased at connections, especially with higher amounts of screws. Otherwise, adding extra screws has an insignificant effect to the capacity of the connection. In summary, characteristics, trends and failure analysis of the connections will allow for improvements in the connections to enhance design of the trusses under blast loads.

# 5 TrusSteel Connections

## 5.1 Preface

Similar to the Aiges Connections, our goal will be to test and characterize the connections of the TrusSteel cold form steel roof trusses. Testing will be performed on every connection combination within the TrusSteel full-scale truss. The connections throughout the truss will once again differ by member type, amount of screws and screw spacing. Tension tests using a MTS-Hydraulic Tensile Test Machine will be performed on the connections. In our testing, a connection composed of the web and chord members themselves was created. No substitution plates were used in this test. The chord member will be fixed at the bottom through a weld to an assembly that will be pulled in tension. The web member will be connected to the gripping plates through the use of bolts. This will allow for an accurate simulation of how the screw connection will behave within the full-scale truss. The testing will provide the stiffness, deflection, load capacity and other connection properties. These properties will be input into the full scale numerical model. The tests will also give insights on types of failure that occur in different connections and the causes of the failures.

## 5.2 Research Method

### 5.2.1 Background

This section discusses the different materials that are used in both the actual trusses and in the connection test. The TrusSteel truss members are also made from cold formed steel and are held together by self-tapping screws. The trusses that are being tested consist of 9 members. There are 4 chord members and 5 web members that vary by size and thickness. Different chord and web members are used in different trusses that are being tested. TSC sections are chord members, while W sections are web members. Shown in the figures below are the dimensions of chord and web members and how they differ from each other.

5.2.2 Chord Members

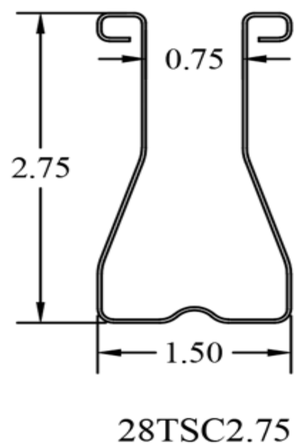



Figure 48: 28TSC Chord Member

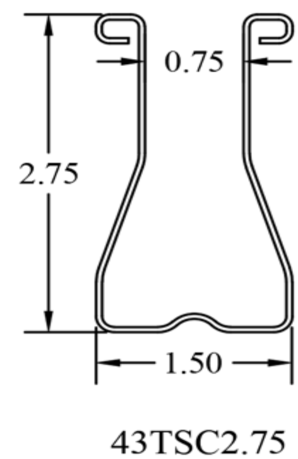



Figure 49: 43TSC Chord Member

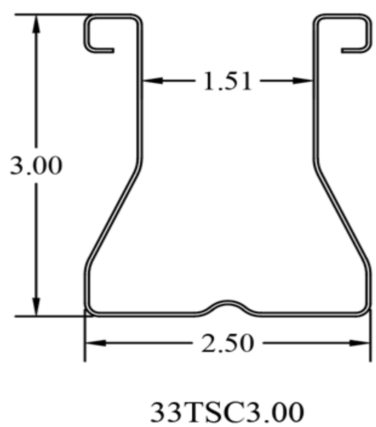



Figure 50: 33TSC Chord Member

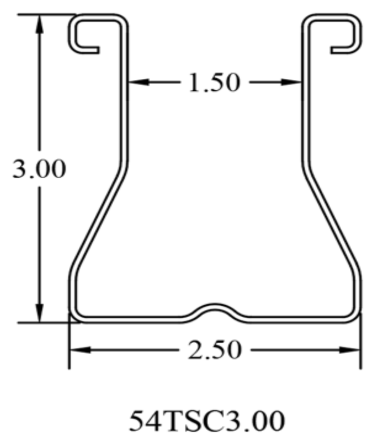



Figure 51: 54TSC Chord Member

As seen above, the TSC members are chord members that are differentiated by their heights and thicknesses in inches. They also have different material properties.

5.2.3 Web Members

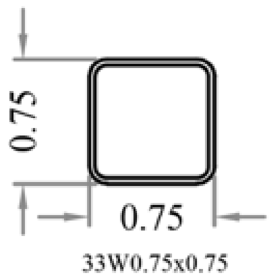



Figure 52: 33W0.75x0.75 Web Member

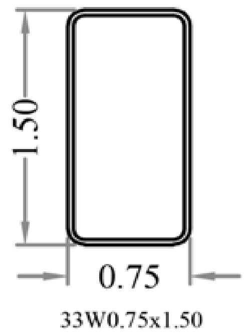



Figure 53: 33W.075x1.50 Web Member

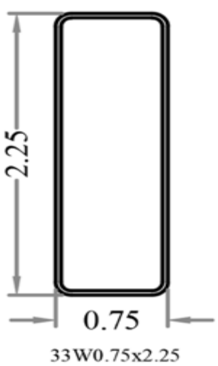



Figure 54: 33W0.75x2.25 Web Member

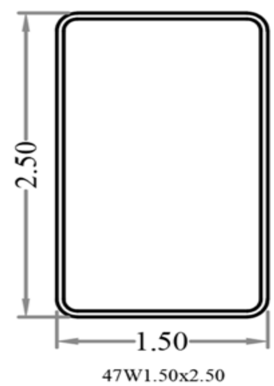



Figure 55: 47W1.50x2.50 Web Member

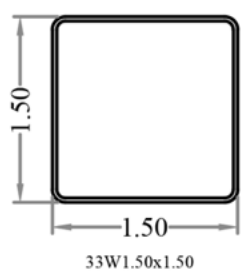



Figure 56: 33W1.50x1.50 Web Member

Shown above are the W web members. They are also differentiated by different material characteristics, dimensions and thicknesses.

### 5.2.4 Connection Matrix

Connections throughout the trusses differ due to members composing the connection, amount of screws and location of the screws. To obtain the required results, all connections in the truss must be tested. Table 11 is the test matrix for all member compositions and screw amounts. It shows each connection's chord member, web member and number of screws. This matrix accounts for all connections in the truss.

| **Chord Section** | **Web Section** | **# of Screws** | **Notation of Samples** |
|---|---|---|---|
| 1: 28TSC275 | 5: 33W.75x.75 | 1 | 028-33W75x75-1 |
| | | 2 | 028-33W75x75-2 |
| | 6: 33W.75x1.5 | 3 | 028-33W75x150-3 |
| | | 4 | 028-33W75x150-4 |
| | | 5 | 028-33W75x150-5 |
| | 7: 33W.75x2.25 | 3 | 028-33W75x225-3 |
| 2: 43TSC275 | 5: 33W.75x.75 | 1 | 043-33W75x75-1 |
| | | 2 | 043-33W75x75-2 |
| | 6: 33W.75x1.5 | 2 | 043-33W75x150-2 |
| | | 3 | 043-33W75x150-3 |
| | | 4 | 043-33W75x150-4 |
| | 7: 33W.75x2.25 | 4 | 043-33W75x225-4 |
| | | 5 | 043-33W75x225-5 |
| 3: 33TSC300 | 6: 33W.75x1.5 | 1 | 033-33W75x150-1 |
| | | 2 | 033-33W75x150-2 |
| | | 3 | 033-33W75x150-3 |
| | | 4 | 033-33W75x150-4 |
| | 8: 33W1.5x1.5 | 2 | 033-33W150x150-2 |
| | | 3 | 033-33W150x150-3 |
| | | 4 | 033-33W150x150-4 |
| | | 6 | 033-33W150x150-6 |
| 4: 54TSC300 | 6: 33W.75x1.5 | 1 | 054-33W75x150-1 |
| | | 2 | 054-33W75x150-2 |
| | | 3 | 054-33W75x150-3 |
| | 8: 33W1.5x1.5 | 2 | 054-33W150x150-2 |
| | | 3 | 054-33W150x150-3 |
| | 9: 47W1.5x2.5 | 4 | 054-47W150x250-4 |
| | | 5 | 054-47W150x250-5 |
| | | Total | 28 |

Table 11: TrusSteel Connection Test Matrix

## 5.3 Test Setup

5.3.1 Machine Description

The test is conducted on an MTS- Hydraulic Tensile Test Machine. This machine, when in operation, is stationary at the top and has a tensile force pulling at the bottom. The data from the machine readings shows load and deflection of the connection.

5.3.2 Setup Information

In our test setup, the desired web member is attached to the desired chord member using self-tapping screws. The web member is then attached to the two grip and grip transition plates with bolts. The chord member is welded to the lower assembly. This weld is fixed and there is no displacement or failure at this point. The gripping plates and the lower assembly are then attached to the MTS – Hydraulic Tensile Test Machine. The test is performed at a strain rate of -.1 in/min. See Figure 57 and Figure 58.

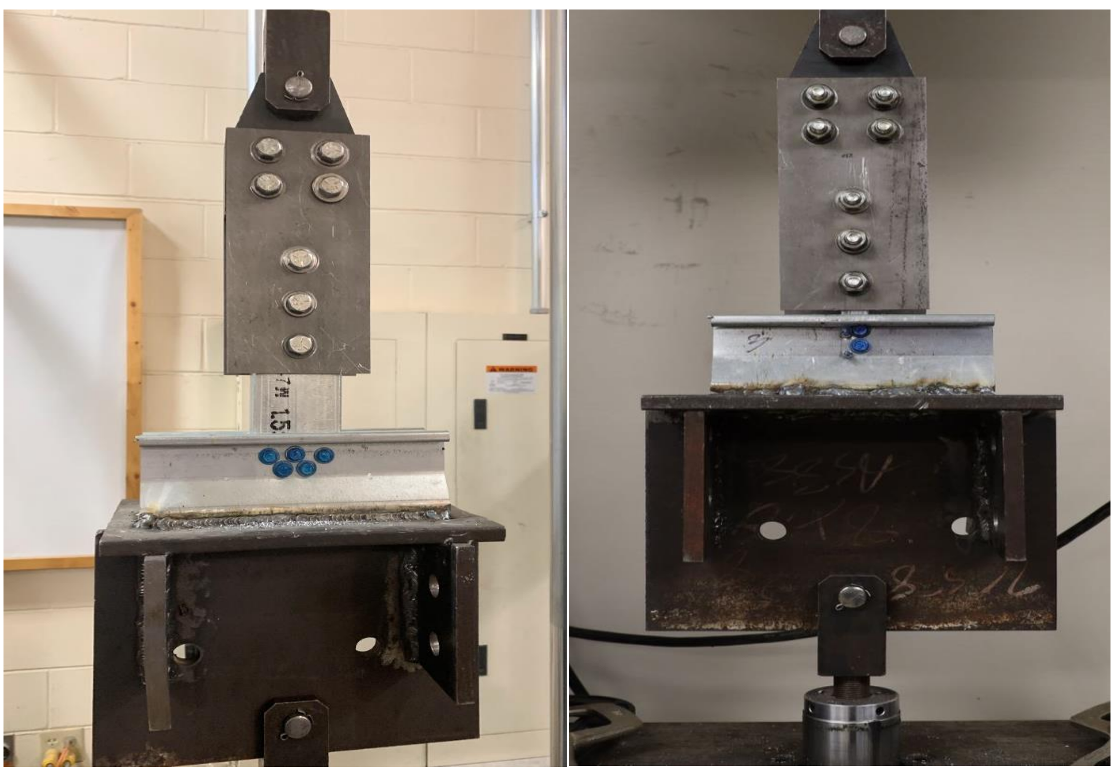


Figure 57: TrusSteel Connection Test Setup Pictures

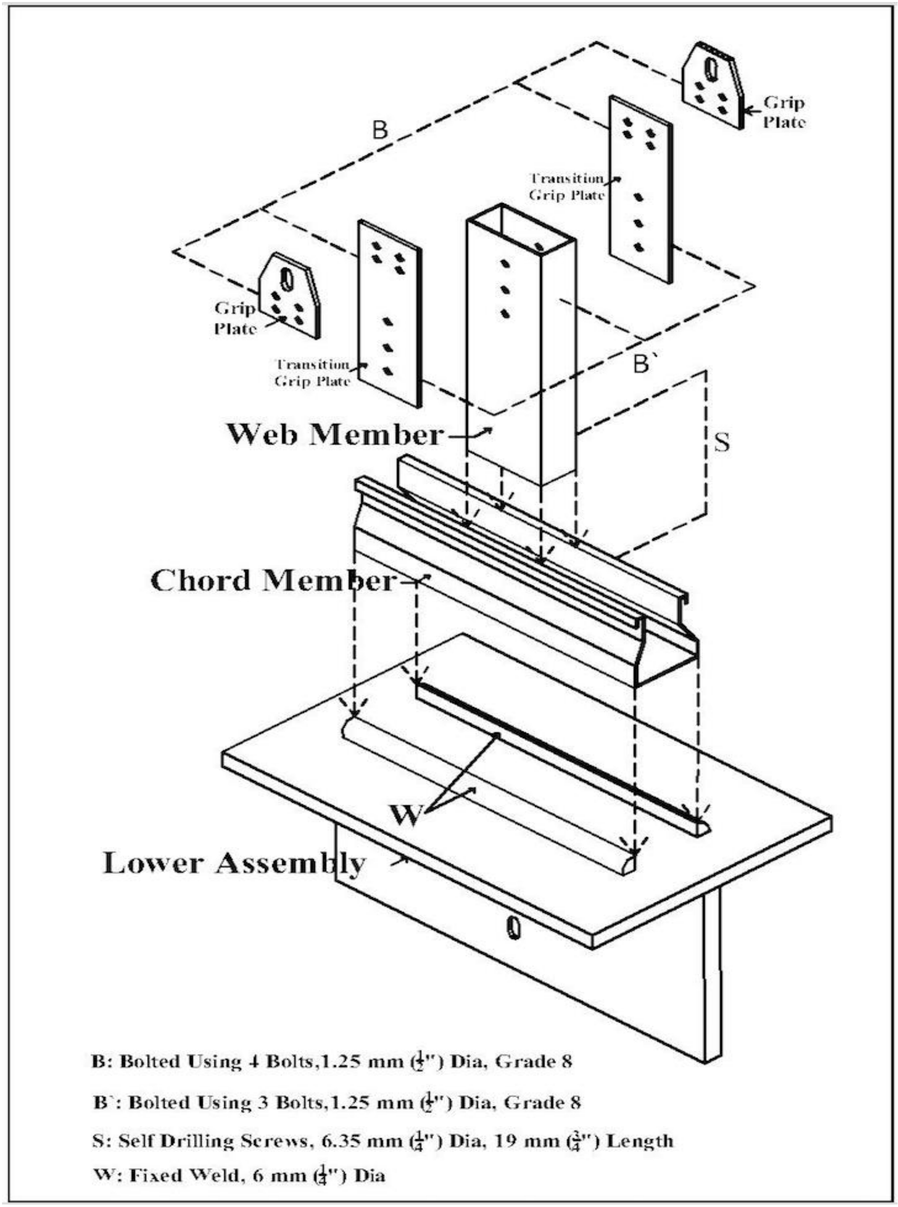



Figure 58: TrusSteel Connection Test Setup

## 5.4 TrusSteel Connection Results & Analysis

In this section, the results for 033-33W150x150 and 054-47W150x250 are shown. An analysis is done on the performance and trends of these connection. A brief comparison will also be done in this section. See Appendix D for all TrusSteel Connection Results.

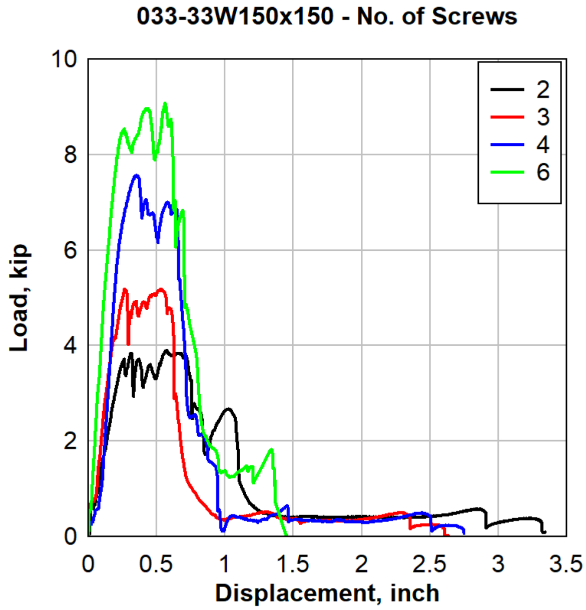



Figure 59: : 033-33W150x150 Results

| Sample | Stiffness (kip/in) | Strain Energy (kip-in) |
|---|---|---|
| 033-33W150x150-2 | 16.19 | 4.07 |
| 033-33W150x150-3 | 25.31 | 3.50 |
| 033-33W150x150-4 | 30.68 | 4.89 |
| 033-33W150x150-6 | 36.08 | 6.32 |

Table 12: 033-33W150x150 Stiffness

The testing of the 033-33W150x150 connection found several important characteristics. First it was found that as the number of screws increases, the peak load increases. The increase proportionality is somewhat dependent on the screw spacing. It is also found that stiffness increases as number of screws increase. Stiffness began at 16.19 kip/in for 2 screws and moved up to 36.08 kip/in for 6 screws. Displacement remains roughly the same despite the number of screws. Strain energy also loosely increases with number of screws, but other factors may cause variations to this loose trend.

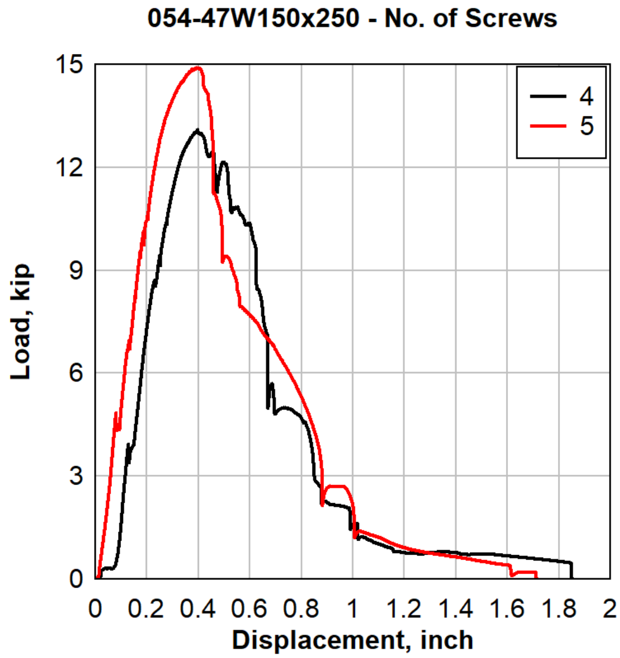



Figure 60: 054-47W150x250 Results

| Sample | Stiffness (kip/in) | Strain Energy (kip-in) |
|---|---|---|
| 054-47W150x250-4 | 62.10 | 7.47 |
| 054-47W150x250-5 | 63.51 | 8.41 |

Table 13: 054-47W150x250 Stiffness

The testing of the 054-47W150x250 connection found a similar trend of the capacity and the stiffness rising with increased number of screws. The stiffness did not rise proportionally as the previously mentioned test due to factors such as screw spacing and different failure type. The results of this test due however show that capacity and stiffness increase due to the strength and thickness of the material. The 4 screw connection of the 033-33W150x150 showed a peak load of approximately 7 kip and a stiffness of 30.68 kip/in. The 4 screw 054-47W150x150 connection showed a peak load of approximately 13 kip and a stiffness of 62.10 kip. The differences where the thicknesses and strength of the member composing the connections. It is fair to conclude that stronger, thicker members will lead to higher peak load and stiffness of the connections.

Below, in Table 14, are the stiffness and peak load results for all TrusSteel connections. The trend of load and stiffness increasing with number of screws can be seen in the overall results. The trend of strain energy loosely increasing can also be seen.

| Notation of Samples | Stiffness (kip/in) | Peak Load (kip) | Strain Energy (kip-in) |
|---|---|---|---|
| 028-33W75x75-1 | 47.91 | 1.9 | 1.19 |
| 028-33W75x75-2 | 82.92 | 3.2 | 2.14 |
| 028-33W75x150-3 | 42.48 | 4.9 | 3.29 |
| 028-33W75x150-4 | 47.29 | 6.6 | 3.59 |
| 028-33W75x150-5 | 54.44 | 8.0 | 3.40 |
| 028-33W75x225-3 | 29.44 | 5.0 | 3.68 |
| 043-33W75x75-1 | 18.95 | 2.4 | 1.95 |
| 043-33W75x75-2 | 31.25 | 4.7 | 1.13 |
| 043-33W75x150-2 | 27.85 | 5.0 | 2.83 |
| 043-33W75x150-3 | 35.31 | 7.2 | 2.89 |
| 043-33W75x150-4 | 52.70 | 8.1 | 2.74 |
| 043-33W75x225-4 | 30.84 | 8.9 | 5.91 |
| 043-33W75x225-5 | 38.69 | 9.8 | 3.99 |
| 033-33W75x150-1 | 12.61 | 2.1 | 2.22 |
| 033-33W75x150-2 | 15.04 | 3.6 | 2.29 |
| 033-33W75x150-3 | 21.94 | 6.0 | 4.25 |
| 033-33W75x150-4 | 35.22 | 6.8 | 5.57 |
| 033-33W150x150-2 | 16.19 | 3.9 | 4.07 |
| 033-33W150x150-3 | 25.31 | 5.0 | 3.50 |
| 033-33W150x150-4 | 30.68 | 7.6 | 4.89 |
| 033-33W150x150-6 | 36.08 | 9.0 | 6.32 |
| 054-33W75x150-1 | 10.44 | 2.8 | 2.06 |
| 054-33W75x150-2 | 23.71 | 6.0 | 2.83 |
| 054-33W75x150-3 | 32.07 | 6.8 | 2.88 |
| 054-33W150x150-2 | 22.15 | 5.4 | 3.72 |
| 054-33W150x150-3 | 26.45 | 8.0 | 6.18 |
| 054-47W150x250-4 | 62.10 | 13.0 | 7.47 |
| 054-47W150x250-5 | 63.51 | 15.0 | 8.41 |

Table 14: TrusSteel Results

## 5.5 Discussion and Summary

5.5.1 Discussion

The results found in the TrusSteel connection testing was similar to the results found in the Aiges connection testing. The TrusSteel member experienced an increase in peak load and stiffness as the members composing the connection increased in thickness and strength and as the amount of screws increased, assuming adequate screw spacing. Similarly, to the Aiges connections, a screw concentration could cause a group effect that reduced the effectiveness of the screws.

When it comes to the connection failures, members that have thinner web members then chord members tended to exhibit a material failure in the web member. The web member would predominantly have a bearing and tearing of the material failure, with partial block shear, or full-on block shear failure occurring in rare occasions.

Figure 61: Bearing, Tearing & Partial Block Shear Failures

As per Figure 61, you can see the bearing and tearing of the material. Partial block shear would occasionally be present. This is believed to be due to the screw spacing and pattern. Since the block shear typically happens after the material failure already begins, it is not believed that this will affect the stiffness or peak load of the connection. Shown in Figure 62 is a full block shear failure that would occasionally occur. In these situations, the screw spacing was slightly smaller and the material failure evolved into a block shear failure.

Figure 62: Block Shear Failure

A unique, but noteworthy failure was that of 054-47W150x250-4. This connection was composed of a the .054" chord member, and a .047" web member. All other TrusSteel web members were .033". Since this connection was composed of a stronger web member. it exhibited a combined failure of shear failure of the screws and a block shear failure. As seen in Figure 63, the screws experienced a shear rupture on the back half of the connection while the block shear failure happened in the front of the connection. This was the only connection to experience this type of failure.


Figure 63: 054-47W150x250 Failure

When chord members where thinner and weaker than web members, typically a material failure of the chord member would occur. The failure was usually a bearing and tearing failure, but occasionally showed some signs of block shear failure along with the bearing and tearing. The failure would typically see the folded lip of the chord act as resistance and increase the displacement of the final failure were the connection reached a load of zero kips. This case typically applied to the 28TSC chord member tests. See Figure 64 for the visual of the bearing, tearing and block shear failures.

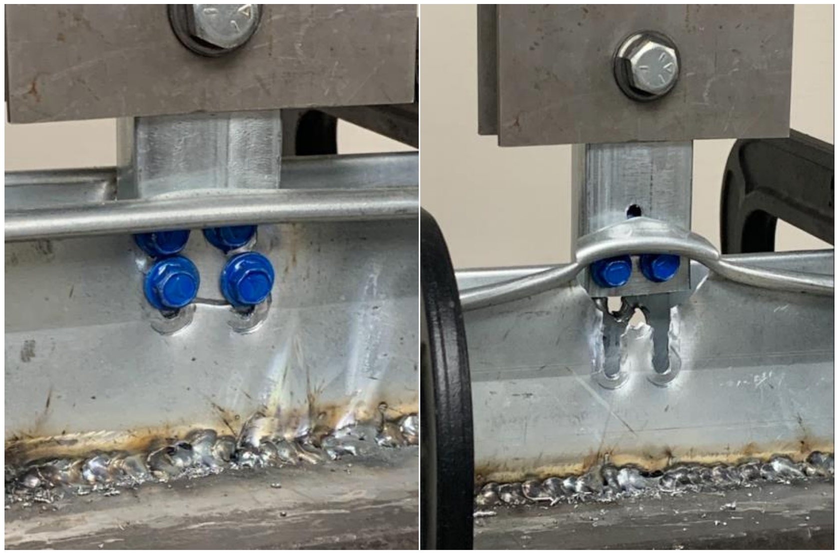


Figure 64: Thinner Chord Member Bearing, Tearing and Block Shear Failure

When chord and web members were composed of similar thickness and strength materials, the failure was much more unpredictable. It occurred in the chord, web, both and occasionally even in the screws. The failure was typically a material failure, but in one case there was a shear failure of one of the screws. When the failure of the material occurred in the chord, a similar phenomenon of the lip bending and causing a large displacement occurred. See Figure 65 for all failures mentioned.

Figure 65: Similar Member Failure Types

There were also cases where there was extremely high screw concentration that disrupted the proportionality of the load to screw ratio. An example of this was in the 033-33W150x150-6 connection. In this case, the load and the stiffness were not proportional with the number of screws. This connection had material and block shear failure in the chord, material, and rupture of the side of the member in the web, and even large bearing failure at the bolt holes. The screw spacing on this connection should be increased for greater results from the screws. See Figure 66.

Figure 66: 033-33W150x150-6 Failures

### 5.5.2 Summary

To summarize, similarly to the Aiges results, the conducted test results will be used in conjunction with the numerical model for full-scale truss testing. Connection characteristics such as load capacity, displacement and stiffness will be applied to the numerical model to enhance the results and improve the viability of the simulation. Several key findings were also made in this test. First, TrusSteel connections utilize screws in double shear which allow for higher connection characteristics then that of Aiges. Second, increasing the number of screws causes an increase in load capacity, decreases displacement, and increases stiffness. Third a study of failure types such as bearing & tearing, block shear and screw failure in our connections was performed. Different variables such as number of screws, screw spacing and materials composing the connection were analyzed to study the type of failure that occurs. Similarly, to Aiges testing, it was found that screw spacing caused stress concentration and a group effect that resulted in a loss of proportionality between load, stiffness and number of screws. This leads to the same recommendation that screw spacing be increased at connections, especially with higher amounts of screws. The testing of the Aiges connections also saw a similar trend of peak load and stiffness increasing with number of screws outside of scenarios with high screw concentration. Overall, the two tests had many similar findings. Finally, characteristics, trends and failure analysis of the connections will allow for improvements in the connections to enhance design of the trusses under blast loads.

# 6 End Bearing Connections

## 6.1 Preface

The objective of this chapter is to test the end bearing connections of the Aiges and TrusSteel trusses. Testing of the full-scale trusses showed that end bearing connections where a common cause of failure of the truss. Improvements of the end bearing connections could lead to a much better performing truss. The tests will provide us results on the properties and failure types of the end bearing connections. The results will then be input into the numerical models and used to improve the full-scale trusses by improving the end bearing connections. To perform this, a tension test using a MTS-Hydraulic Tensile Test Machine will be performed on the end bearing connections. The test will be on the horizontal direction of the end bearing connections due to the fact that it has a large majority of the impact of the forces and behavior of the connection. The testing results will focus on the stiffness, deflection, load capacity and failure types. These properties will be input into the full scale numerical model. The tests will also give insights on types of failure that occur and the causes of the failures.

## 6.2 Aiges Research Method & Setup

### 6.2.1 Research Method

All members of the Aiges trusses remain similar to the ones mentioned in Chapter 3-4. The end bearing test, however, only uses certain web members and uses substitution plates to replace chord members. End bearing connections are also cut into plates and used as substitution for the end bearing connection. These substitution plates are used to allow for an achievable testing setup, while still maintaining the integrity of the end bearing connection. The test matrix will show the chord substitution plate, web member, and number of screws. All end bearing connection substitution plates are the same since they are made directly from the end bearing connection. See Table 15 for the Aiges End Bearing Test Matrix.

| Chord Substitution Plate (in) | Web Member | Screws |
|---|---|---|
| .035 | USW035 | 7 |
| | | 12 |
| | USW057 | 7 |
| | USWD035 | 7 |
| | | 9 |
| | USWD046 | 10 |
| .046 | USW046 | 7 |
| | USWD046 | 10 |

Table 15: Aiges End Bearing Test Matrix

The test matrix is composed of member and screw combinations that are apart of actual end bearing connections in the full-scale trusses.

6.2.2 Test Setup

The test is conducted on an MTS- Hydraulic Tensile Test Machine. This machine, when in operation, is stationary at the top and has a tensile force pulling at the bottom. The data from the machine readings shows load and deflection of the connection.

In our test setup, the desired web member is attached to the end bearing plate and the desired chord substitution sheet using self-tapping screws. The screw locations varied depending on the amount of screws, and the type of web member used. There are always 4 screws between the web member and the bearing connection plate. The substitution plates are joined with filler plates and attached to the gripping plate, which is then attached to the MTS Machine. The test is performed at a strain rate of .1 in/min. See Figure 67 for a diagram of the Aiges end bearing connection setup.

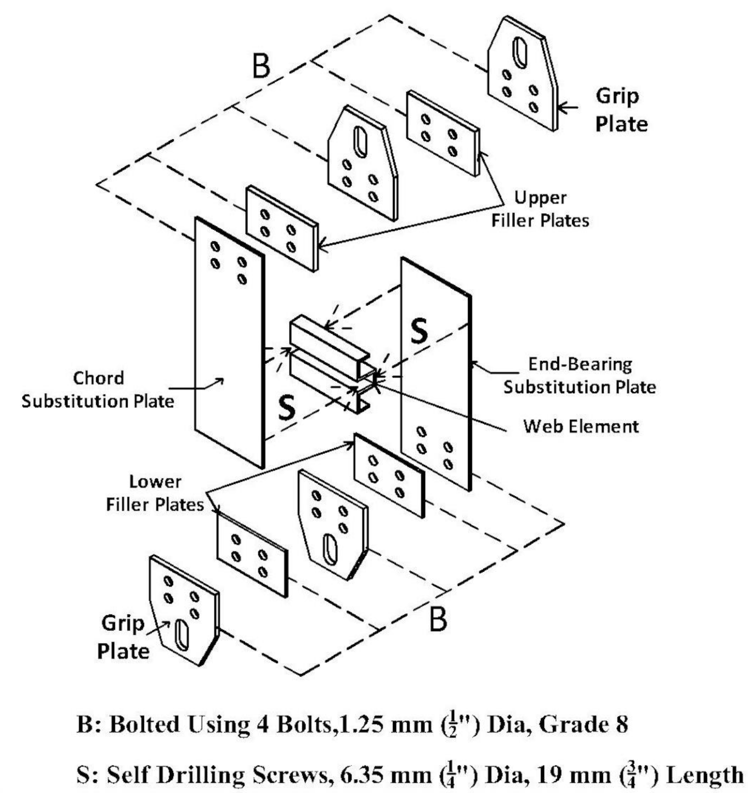



Figure 67: Aiges End Bearing Connection Setup

## 6.3 TrusSteel Research Method and Setup

6.3.1 Research Method

All members of the TrusSteel trusses remain similar to the ones mentioned in Chapter 3 and 5. The end bearing test, however, only uses two chord members, the 43TSC and 54TSC. There is no test matrix for this section because there are only two tests and no differences between the two tests besides the chord member.

6.3.2 Test Setup

Similarly, to Aiges, the test is conducted on an MTS- Hydraulic Tensile Test Machine at a strain rate of .1 in/min. In our test setup, we use an L-shaped loading transition arm so that the connection has no eccentricity. The location of loading in the top must be in line with the location of loading at the bottom, or there will be a moment on our connection. Since testing concerns only the horizontal aspect of the end bearing connection, a chord member is the only thing that will be tested. A vertical plate is welded onto the lower assembly and the end bearing connection is attached to this assembly through the use of a ¼" weld. The end bearing connection is then attached to the chord member using 12 screws, 6 on each side. The chord member is then attached to the loading transition arm and filler plates through the use of bolts. The loading transition arm and lower assembly are then attached to the machine. See Figure 68 for a diagram of the TrusSteel end bearing setup.

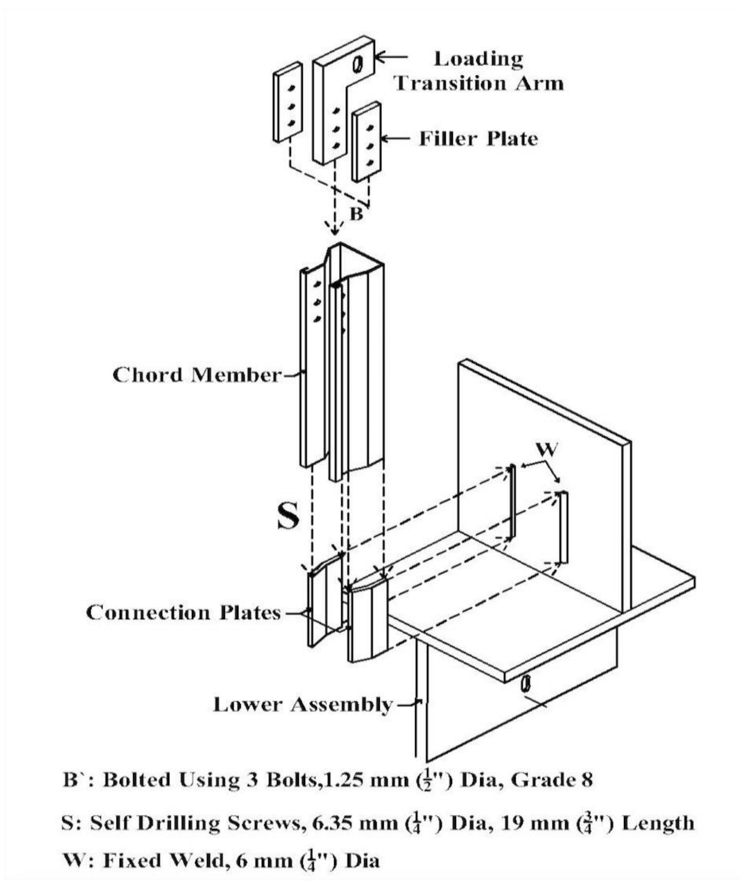



Figure 68: TrusSteel End Bearing Connection Setup

## 6.4 Results and Analysis

This section will provide the key results of the Aiges and TrusSteel end bearing connections. It will also give a brief analysis of the results and potential trends that occur. See Appendix E for remaining end bearing results.

6.4.1 Aiges

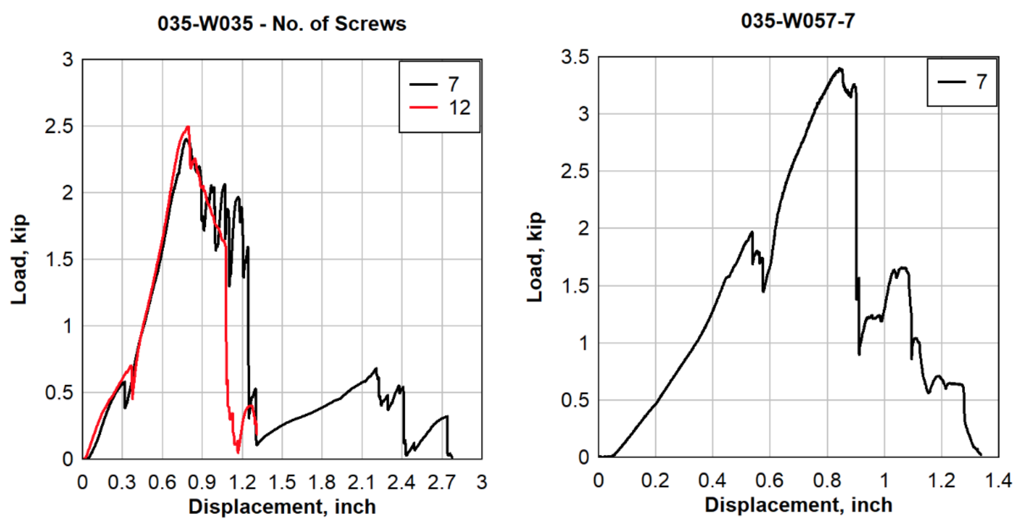



Figure 69: Aiges End Bearing Key Results

After conducting testing of the Aiges end bearing connections, it was found that amount of screws had minimal impact on the peak load of the end bearing connection. This occurred in USW and USWD connections. As seen in Figure 69 the peak load capacity of 2.5 kip does not change whether 7 or 12 screws are used. This trend is similar in other testing found in Appendix E. It was, however, found that changing the thickness of the web member did have significant impact on the peak load of the connection. As seen in Figure 69, when increasing from a USW035 to a USW057, the peak load increased from approximately 2.5 kip to approximately 3.5 kip. This trend also holds throughout other end bearing connections tested that can be found in Appendix E.

| Sample | Stiffness (kip/in) |
|---|---|
| 035-W035-7 | 2.22; 4.34 |
| 035-W035-12 | 2.15; 5.00 |
| 035-W057-7 | 4.00; 6.49 |
| 046-W046-7 | 2.49; 5.65 |
| 035-WD035-7 | 0.82 |
| 035-WD035-9 | 0.87 |
| 035-WD046-10 | 1.29 |
| 046-WD046-10 | 1.29 |

Table 16: Aiges End Bearing Stiffness

The stiffness of the Aiges end bearing connection is mostly dependent on the web member used. The screw amount has a small effect on the stiffness. This can be seen in Table 16. As screw spacing changes, stiffness increases slightly, but as the web member changes, stiffness increases greatly. The stiffness of the USW members ranges from 2.15 kip/in to 6.49 kip/in, while the USWD members have stiffness values that range from .82 kip/in to 1.29 kip/in. The USW member connections have multiple stiffness values during the failure.

6.4.2 TrusSteel

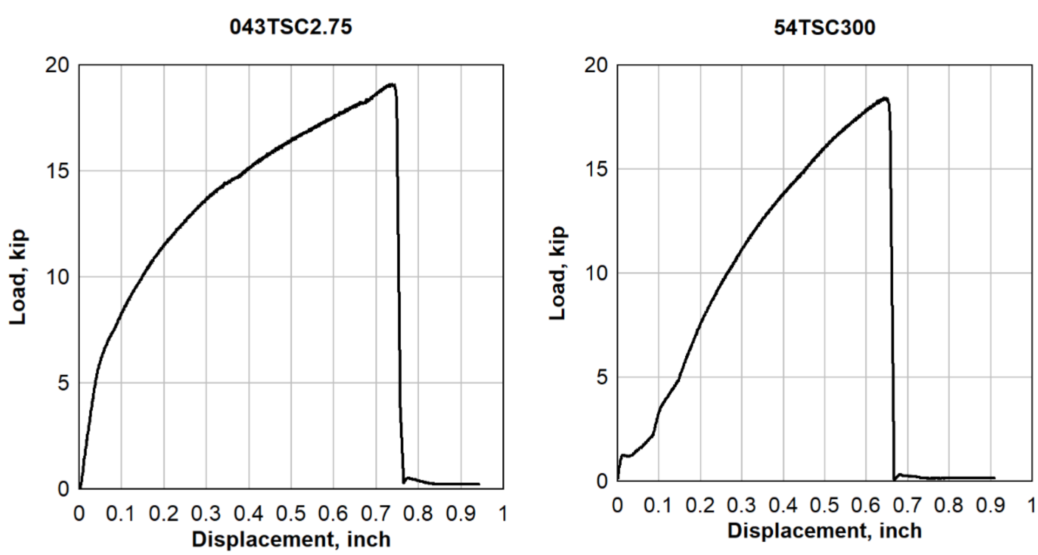



Figure 70: TrusSteel End Bearing Results

Both TrusSteel end bearing connections experienced similar results. The 043TSC275 failed at approximately 19 kip while the 54TSC300 failed at approximately 18 kip. See Figure 70.

| Sample | Stiffness (kip/in) |
|---|---|
| 043TSC275 | 139.49 |
| 054TSC300 | 125.51 |

Table 17: TrusSteel End Bearing Stiffness

The stiffness of the end bearing connection paints a similar comparison. The stiffness of the 043TSC275 was 139.49 kip/in and the stiffness of the 054TSC300 was 125.51 kip/in. Both end bearing connections had similar stiffness values. The 043TSC275 was slightly greater. The 043TSC275 value having a slightly greater peak load and stiffness could be either due to error, or due to the fact that the 043TSC275 had a higher yield stress then the 054TSC300.

## 6.5 End Bearing Discussion and Summary

### 6.5.1 Aiges Discussion

The Aiges end bearing connections were found to be highly dependent on the web member. The web member had major impacts on the stiffness, peak load and type of failure that occurred in the connection. During the test, the substitution plates would bend and cause a rotation of the web member. The web member would also bend and deform during the test. The thicker the web member was, the better the ability of it to resist bending, deformation and tendency to rotate. This resulted in the end bearing connection having a greater stiffness and load. See Figure 71 for image of rotation tendencies.

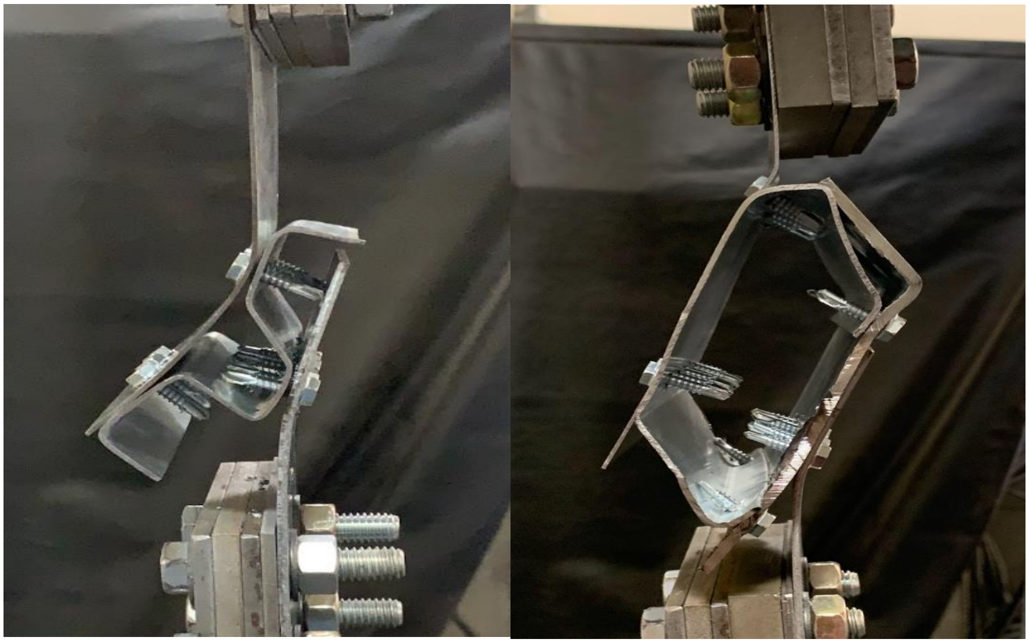


Figure 71: Aiges End Bearing Rotation

The web member also had a large impact on the type of failure. The screw amount, however, also had an impact on the failure type. Seen in Figure 72 are three connection failures. The left picture shows a USW057 with 7 screws, the middle picture shows a USW035 with 12 screws and the right picture shows a USW035 with 7 screws.

Figure 72: End Bearing USW Failure Types

As seen, the W057 with 7 screws failed due to screw shear between the end bearing plate and the web member. The W035 with 7 screws however failed due to pull-out failure between the chord substitution plate and the web member. When increasing up to 12 screws, the failure went back to screw shear failure between the web member and the end bearing plate. This shows the significance of the web member thickness on the end bearing, but also shows one impact that screw amount has on the connection.

The failure type for the USWD was fairly consistent. The failure always occurred at the 4 screw connection between the web member and end bearing plate. The web member affected the peak load and stiffness of the connection, but not the failure type.

Figure 73: USWD End Bearing Failure

The number of screws had little effect on the USWD end bearing connections because the failure typically happened at the 4 corner screws. See Figure 73 for a picture of a typical USWD end bearing failure.

6.5.2 TrusSteel Discussion

The failure for both types of TrusSteel end bearing connections was a shear failure of the screws. The chord member had little effect on the performance of the connection.


Figure 74: TrusSteel End Bearing Failure

As seen in Figure 74, all 6 screws on both sides, 12 total, failed in shear. No signs of bearing and tearing are seen in the connection.

6.5.3 Summary

In summary, similar to the results of the standard connection, these results will be used with the numerical model of the full-scale truss. The peak load and the stiffness of the connections will be input into the numerical model to improve the results. Key findings in the end bearing connection testing where that in Aiges end bearing testing, the web member used had a drastic impact on the performance of the end bearing connection. The screw amount had a small impact, but not nearly as much as the web member used. The web member used effected the type of failure, the stiffness and the peak load. In the TrusSteel end bearing test, it was found that the failure that occurred was a shear failure of screws and the chord member used had only a small impact on the behavior of the end bearing connection. These findings lead to the recommendation of increasing the thickness of the web member for Aiges connections. If the web member thickness is increased, the end bearing connection will perform better and as a result the full-scale truss will have an increased performance. This will result in an enhanced end bearing connection and full-scale truss that will perform better under blast loads.

# 7 Conclusions & Recommendations

The research presented in this thesis focused on the experimental evaluation of connections used in the construction of CFS roof truss systems. Truss connections from two different manufacturers were utilized in this study. The connection testing program was performed to provide valuable input parameters needed for developing accurate numerical simulations models of the full-scale roof truss systems. Detailed findings were provided in individual chapters, and additional conclusions and recommendations for future work are presented next.

## 7.1 Conclusions

In this study, all results found including material characteristics, connection characteristics and end bearing characteristics will be input into a numerical model simulation of full-scale trusses to enhance results. Also, conclusions from each of the 4 chapters will be used to further our understanding and improve the performance of the full-scale trusses under blast loads.

- Material characteristics at different locations throughout the member have little impact on the material characteristics.
- It was found that the cold rolling process results in changes to material properties. The cold rolling may cause the steel to yield and enter plastic deformation, such as seen in Member 43TSC275. This will result in higher yield stress, lower strain, and much less strain energy of the material. This results in a truss that does not behave in as ductile of a fashion under blast loads.
- Increasing the number of screws increases load capacity and stiffness, while decreasing the displacement.

- Decreased screw spacing causes a group concentration effect that reduced the load and stiffness of the connection in proportion to the number of screws.
- Both connections exhibit bearing & tearing failure. Aiges experiences tilting and pull-out; TrusSteel experiences block shear and shearing of screws.
- In the Aiges end bearing connections, the web member had drastic impacts and the screw spacing had a small impact on the performance of the end bearing connection. It was found that the web member influenced the load, stiffness and type of failure.
- In the TrusSteel end bearing test, it was found that shear failure of the screws was the main source of failure. Changes to the chord member only had a small impact on the behavior of the connection.
- TrusSteel member fail in double shear, which results in, on average, more load, stiffness, and strain energy. This results in truss connections that perform better under blast loads.

These findings and trends will allow for recommendations that will lead to the ability for improvements to the performance of the full-scale trusses under blast loads.

## 7.2 Recommendations

From the material testing investigation, it is recommended that the cold forming process and its effects on material characteristics be further tested. It is also recommended that certain members that have already experienced plastic deformation and have low strain energy be upgraded to more ductile members that have not yet been yielded.

From the connection testing, it is recommended that screw spacing be increased at connections, especially in connections that have higher amounts of screws. This will significantly improve the performance of the connections both for Aiges and TrusSteel for higher screw amounts due to the removal of screw concentration group effects.

For the end bearing connections, it is recommended that the web member that is a part of the connection be increased in thickness. This will result in the end bearing connection performing much better when it comes to failure and material properties. It is also recommended that testing on the effects of a layer of epoxy on the Aiges and TrusSteel connections take place. This testing could result in improvements to the performance of the connections. Finally, in the current state of the trusses, it is recommended that TrusSteel trusses be used for blast loads due to the trusses being about to withstand higher peak loads and having larger strain energies. The double shear connections result in a truss with higher material properties and more desirable failures. All these recommendations, I believe, will significantly improve the trusses performance under blast loads.

# References


[1] D. M. Treece, “Experimental Static Resistance of Cold- Formed Steel Roof Truss Systems,” no. April, pp. 1–64, 2022.

[2] ASTM E8, “ASTM E8/E8M standard test methods for tension testing of metallic materials 1,” *Annu. B. ASTM Stand. 4*, no. C, pp. 1–27, 2010, doi: 10.1520/E0008.

[3] D. Lehocka *et al.*, “Effect of pulsating water jet disintegration on hardness and elasticity modulus of austenitic stainless steel AISI 304L,” *Int. J. Adv. Manuf. Technol.*, vol. 107, no. 5–6, pp. 2719–2730, 2020, doi: 10.1007/s00170-020-05191-3.

[4] S. Altai, S. Orton, and Z. Chen, “Evolution of Localization Length during Postpeak Response of Steel in Tension: Experimental Study,” *J. Eng. Mech.*, vol. 146, no. 7, pp. 1–12, 2020, doi: 10.1061/(asce)em.1943-7889.0001804.

[5] S. L. Altai, S. L. Orton, and Z. Chen, “Evolution of post-peak localized strain field of steel under quasi-static uniaxial tension: Analytical study,” *Struct. Eng. Mech.*, vol. 83, no. 4, pp. 435–449, 2022, doi: 10.12989/sem.2022.83.4.435.

[6] H. Rolled, C. R. Steel, and D. There, “Hot Rolled vs Cold Rolled Steel : Overview and Differences What is Hot Rolled Steel ?,” pp. 1–14, 2021.

[7] E. Blog *et al.*, “What ’ s the Difference Between Hot Rolled Steel & Cold Rolled Steel ? Hot Rolled Steel,” pp. 21–24.

[8] N. Abdel-Rahman and K. S. Sivakumaran, “Material properties models for analysis of cold-formed steel members,” *J. Struct. Eng.*, vol. 123, no. 9, pp. 1135–1143, 1997.

[9] H. Chen and P. E. Roger Brockenbrough, “In 2016, AISI S100, North American Specification,” *STRUCTURE*, vol. 9, 2018.

[10] R. A. LaBoube and M. A. Sokol, “Behavior of Screw Connections in Residential Construction,” *J. Struct. Eng.*, vol. 128, no. 1, pp. 115–118, 2002, doi: 10.1061/(asce)0733-9445(2002)128:1(115).

[11] S. F. Sapiee and H. H. Lau, “Influence of screw spacing on the strength of self-drilling screw connection for the high strength cold-formed steel,” *Adv. Mater. Res.*, vol. 712–715, no. 1, pp. 1054–1057, 2013, doi: 10.4028/www.scientific.net/AMR.712-715.1054.

[12] H. H. Lau and S. Y. Tang, "Group effects of multiple self-drilling screws on the connection shear strength for high strength cold-formed steel," in *Proceedings of 11th International Conference on Steel, Space & Composite Structures*, 2012, pp. 249–258.

[13] K. Roy, H. H. Lau, T. C. H. Ting, R. Masood, A. Kumar, and J. B. P. Lim, "Experiments and finite element modelling of screw pattern of self-drilling screw connections for high strength cold-formed steel," *Thin-Walled Struct.*, vol. 145, p. 106393, 2019.

[14] M. Sivapathasundaram and M. Mahendran, "Localised screw connection failures in cold-formed steel roofing systems," *Wei-Wen Yu Int. Spec. Conf. Cold-Formed Steel Struct. 2018 - Recent Res. Dev. Cold-Formed Steel Des. Constr.*, pp. 697–712, 2018.

[15] J. Liu, Q. Liu, and Y. Feng, "Structural behavior of self - Drilling screws applied in steel structures of prefabricated buildings," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 267, no. 5, 2019, doi: 10.1088/1755-1315/267/5/052030.

[16] R. Hongthong, A. Benchaphong, S. Benchanukrom, and N. Konkong, "Experimental and theoretical study on screwed connections in cold-formed steel structure," *Eng. Trans.*, vol. 67, no. 4, pp. 557–577, 2019.

[17] R. M. Francka and R. A. LaBoube, "Screw connections subject to tension pull-out and shear forces," *20th Int. Spec. Conf. Cold-Formed Steel Struct. - Recent Res. Dev. Cold-Formed Steel Des. Constr.*, pp. 635–651, 2010.

[18] W. Yan, T. Mu, Z. Xie, and C. Yu, "Experimental investigation of typical connections for fabricated cold-formed steel structures," *Adv. Struct. Eng.*, vol. 22, no. 1, pp. 141–155, 2019, doi: 10.1177/1369433218781901.

[19] B. Shear, "Chapter 3 - Tension Members," pp. 14–17, 2013.

# Appendix A – TrusSteel Material Results

28TSC275

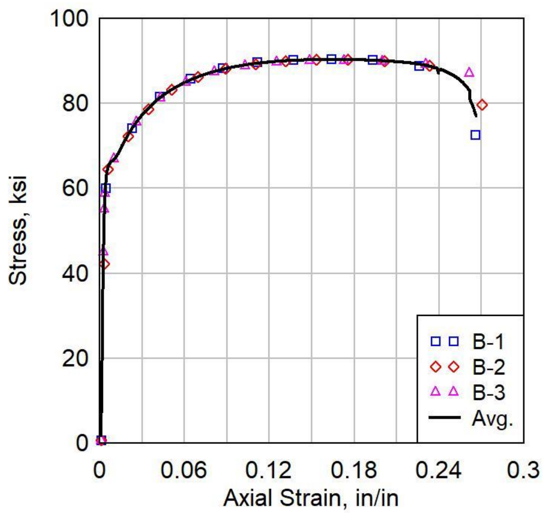



Figure 75: 28TSC275 Large Face

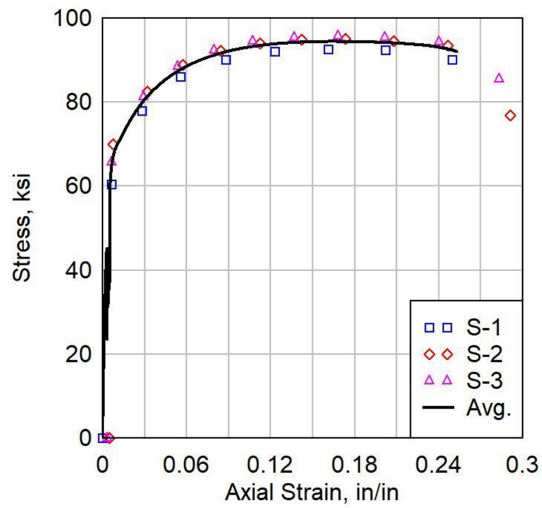



Figure 76: 28TSC275 Small Face

43TSC275

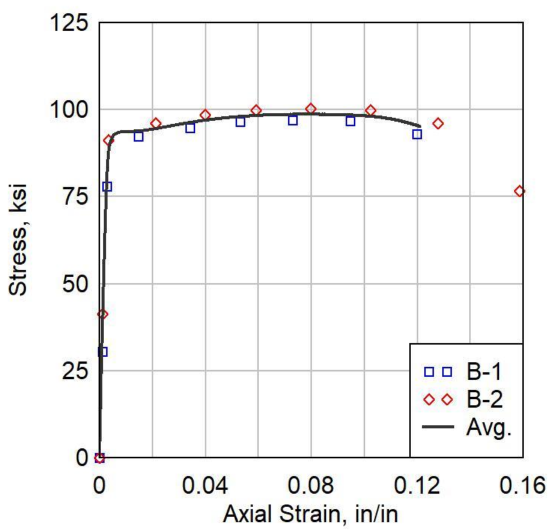



Figure 77: 43TSC275 Large Face

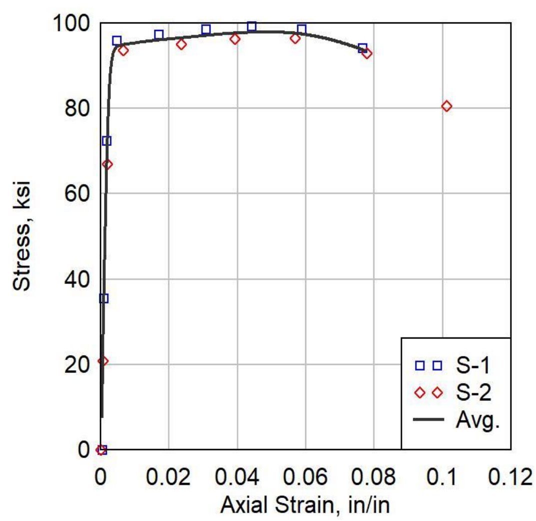



Figure 78: 43TSC275 Small Face

33TSC300

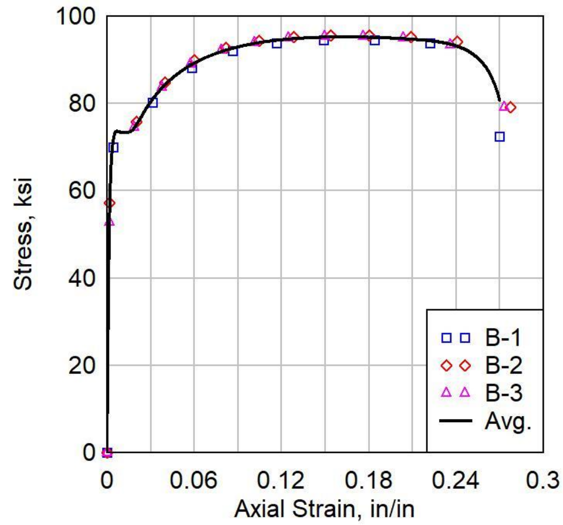



Figure 79: 33TSC300 Large Face

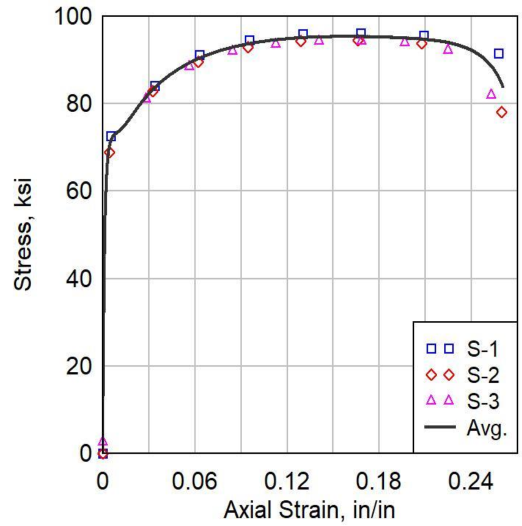



Figure 80: 33TSC300 Small Face

54TSC300

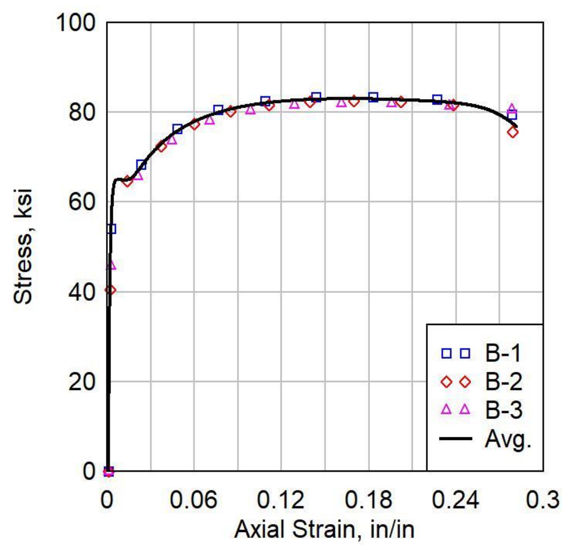



Figure 81: 54TSC300 Large Face

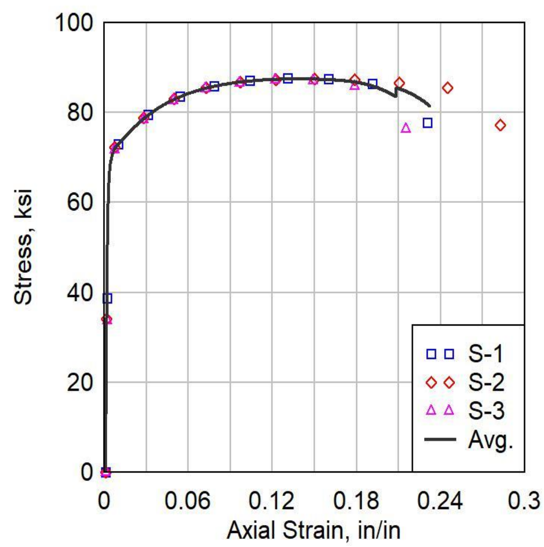



Figure 82: 54TSC300 Small Face

33W.75x.75

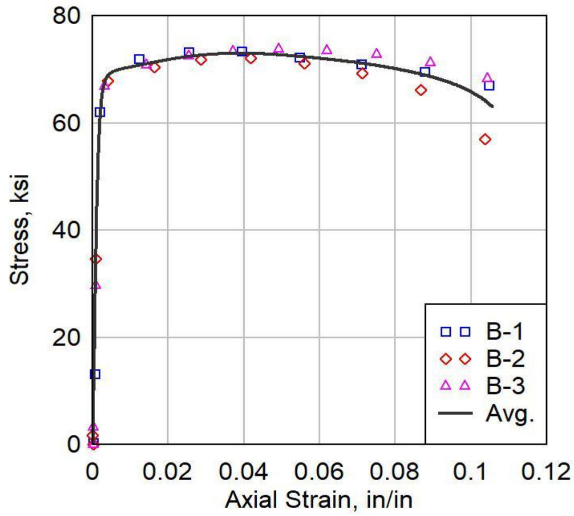



Figure 83: 33W.75x.75 Large Face

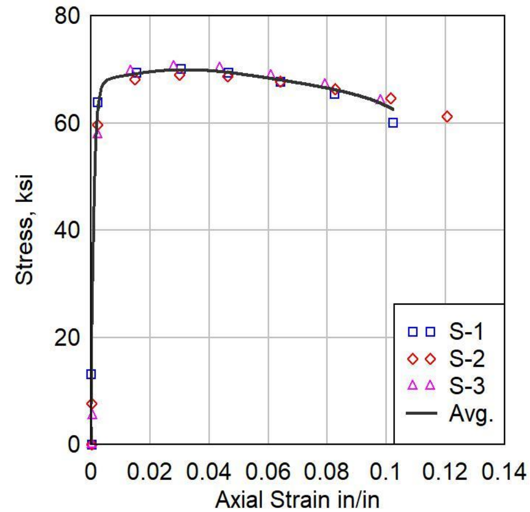



Figure 84: 33W.75x.75 Small Face

33W.75x1.5

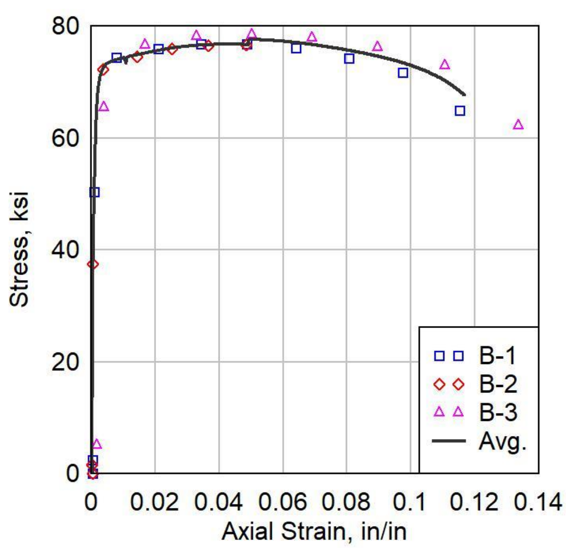



Figure 85: 33W.75x1.5 Large Face

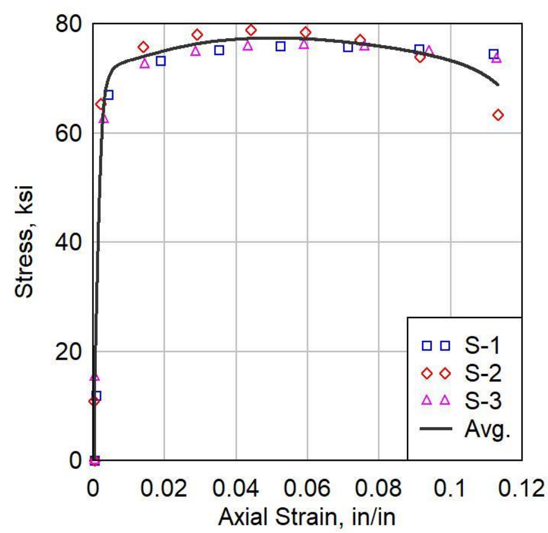



Figure 86: 33W.75x1.5 Small Face

33W.75x2.25

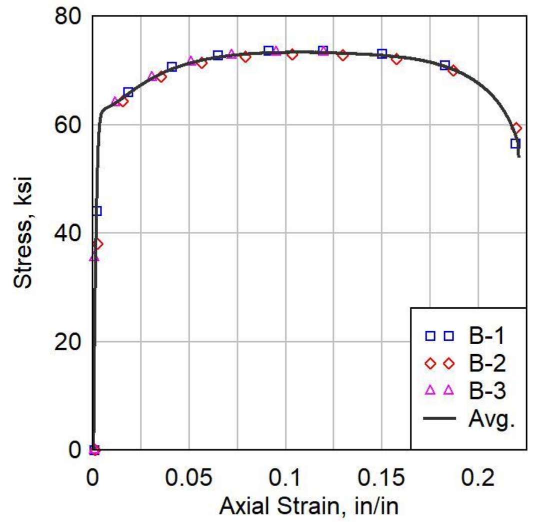



Figure 87: 33W.75x2.25 Large Face

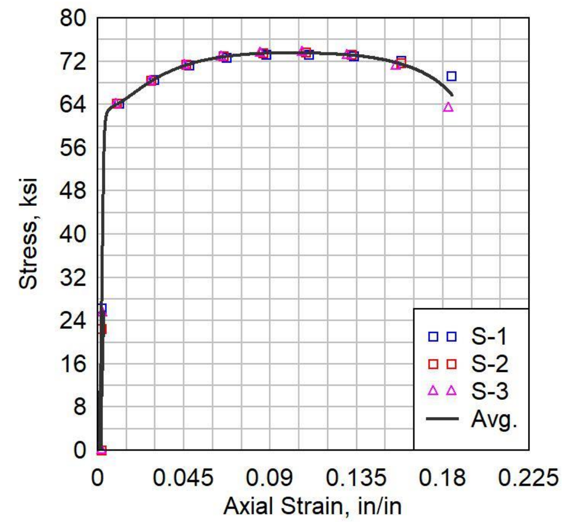



Figure 88: 33W.75x2.25 Small Face

33W1.5x1.5

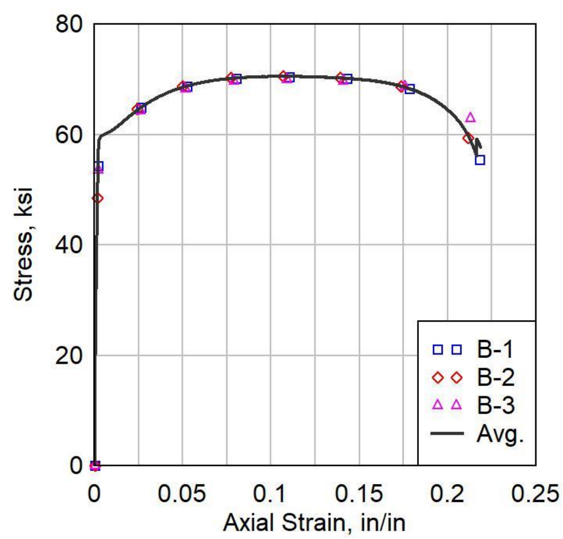



Figure 89: 33W1.5x1.5 Large Face

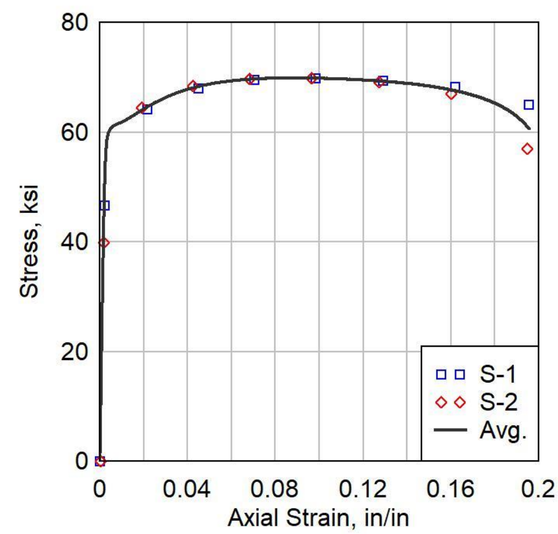



Figure 90: 33W1.5x1.5 Small Face

47W1.5x2.5

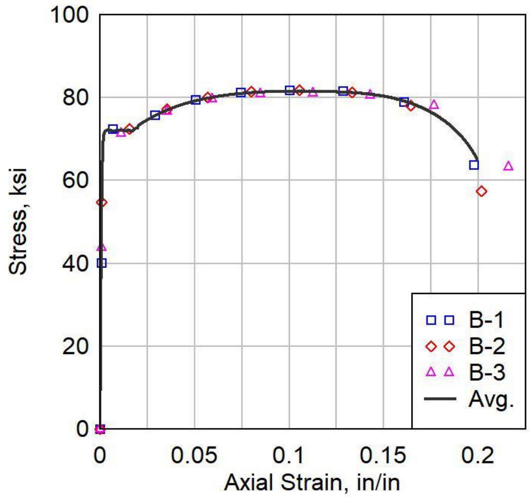



Figure 91: 47W1.5x2.5 Large Face

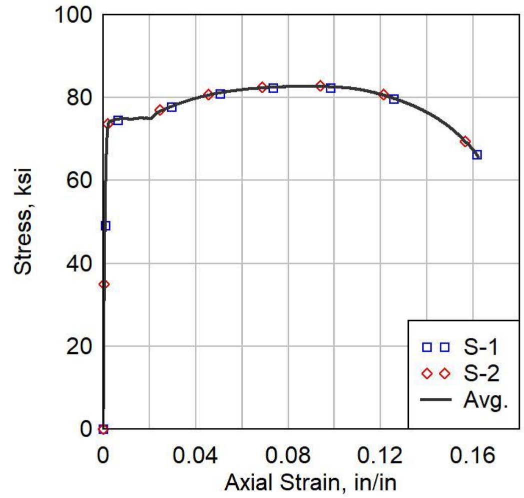



Figure 92: 47W1.5x2.5 Small Face

# Appendix B – Aiges Material Results

<u>362USWD35</u>

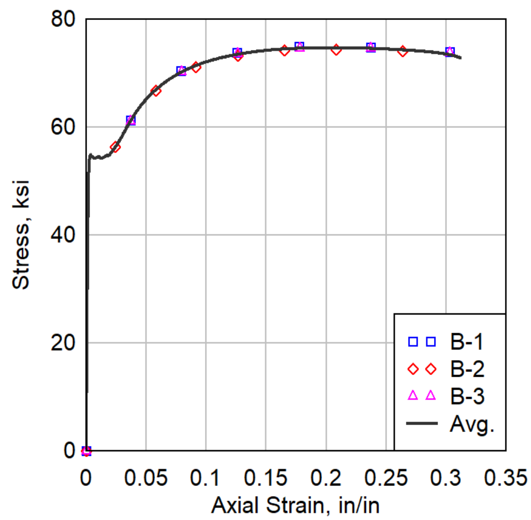



Figure 93: 362USWD35 Large Face

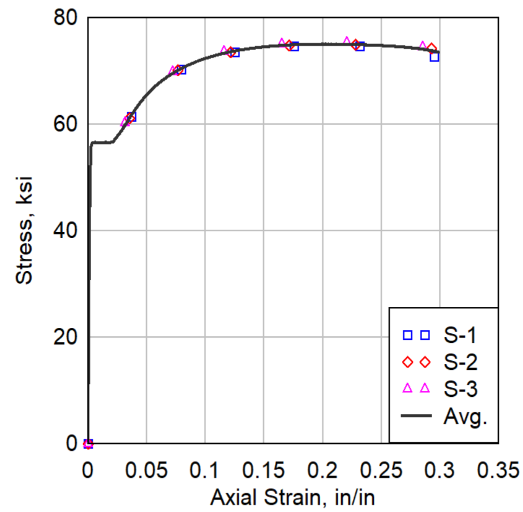



Figure 94: 362USWD35 Small Face

<u>25USWD35</u>

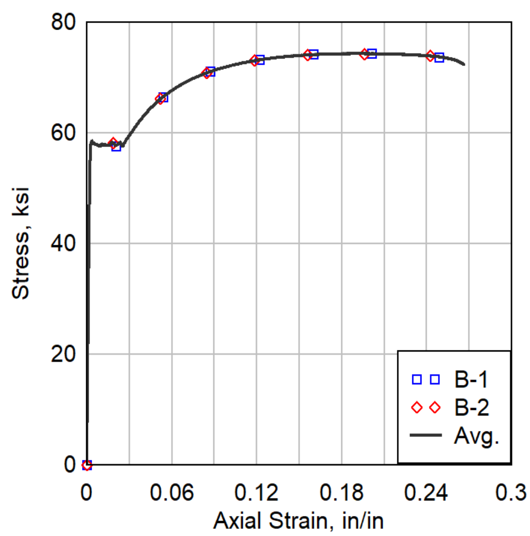



Figure 95: 25USWD35 Large Face

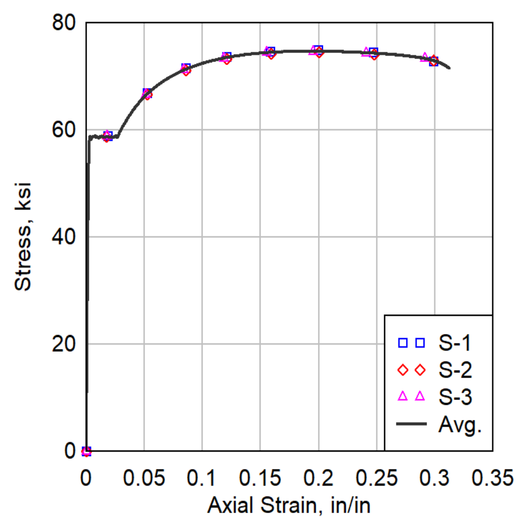



Figure 96: 25USWD35 Small Face

<u>362USWD46</u>

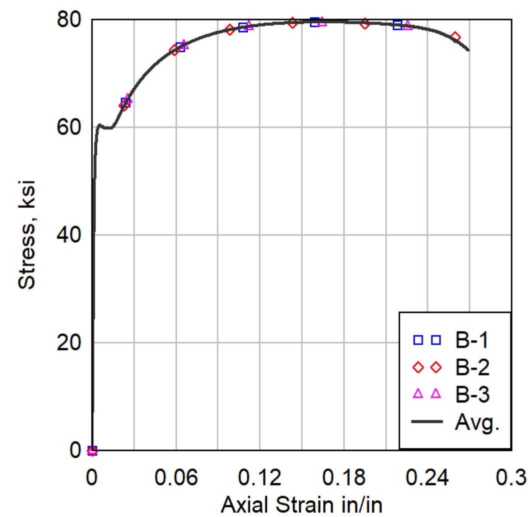



Figure 97: 362USWD46 Large Face

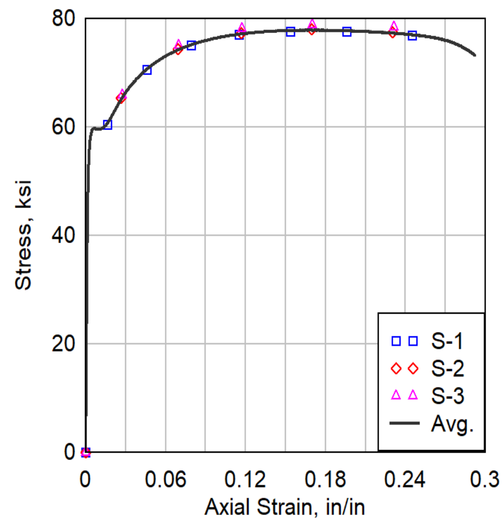



Figure 98: 362USWD46 Small Face

<u>362USWD57</u>

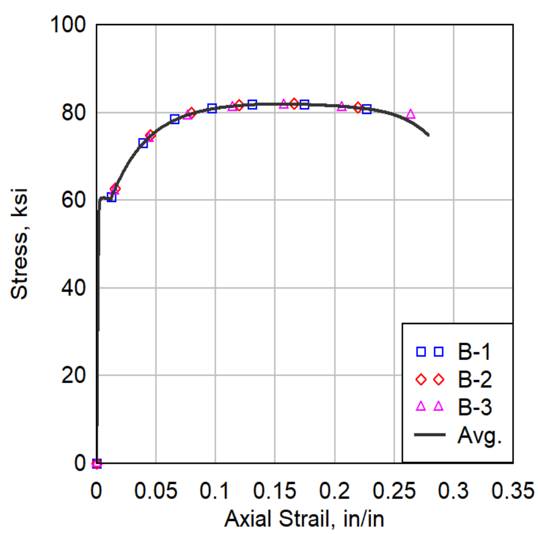



Figure 99: 362USWD57 Large Face

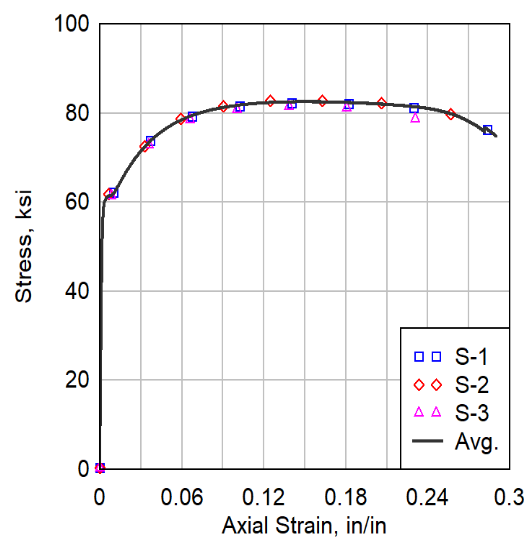



Figure 100: 362USWD57 Small Face

30USW35

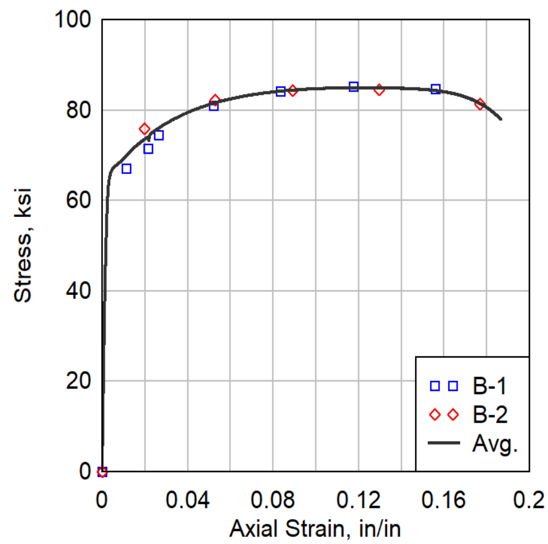



Figure 101: 30USW35 Large Face

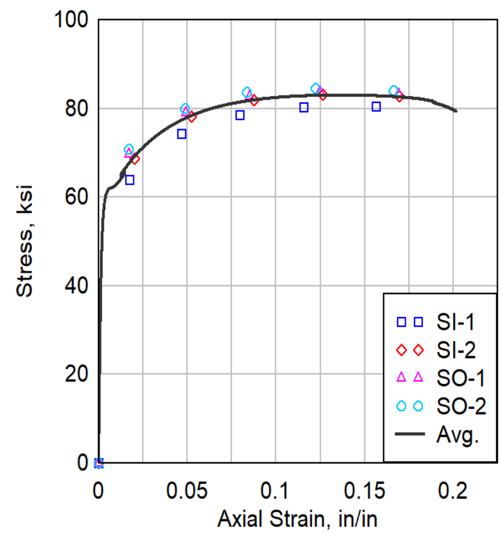



Figure 102: 30USW35 Small Face

30USW46

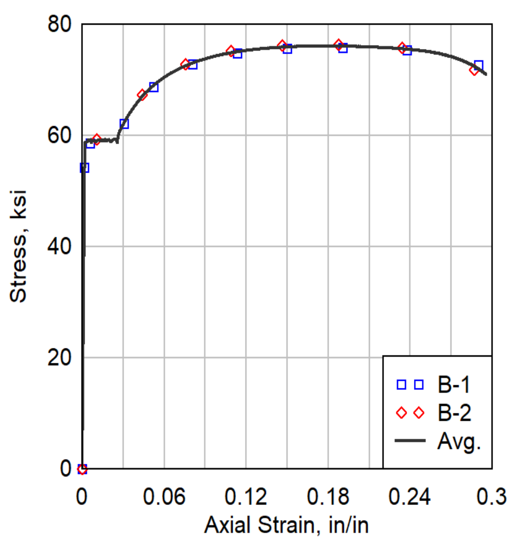



Figure 103: 30USW46 Large Face

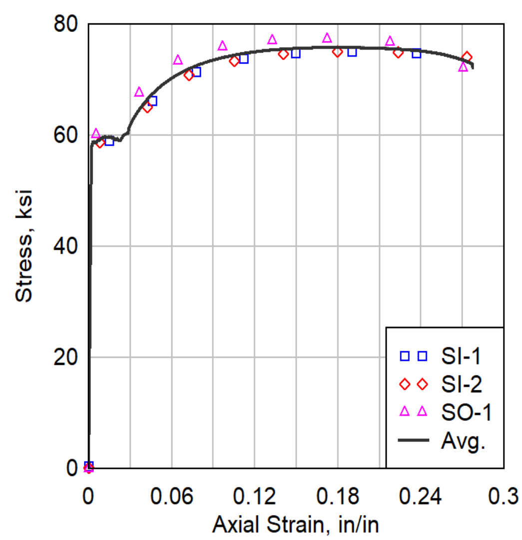



Figure 104: 30USW46 Small Face

30USW57

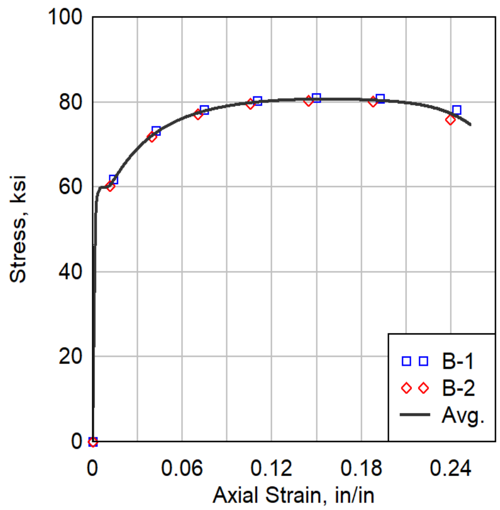



Figure 105: 30USW57 Large Face

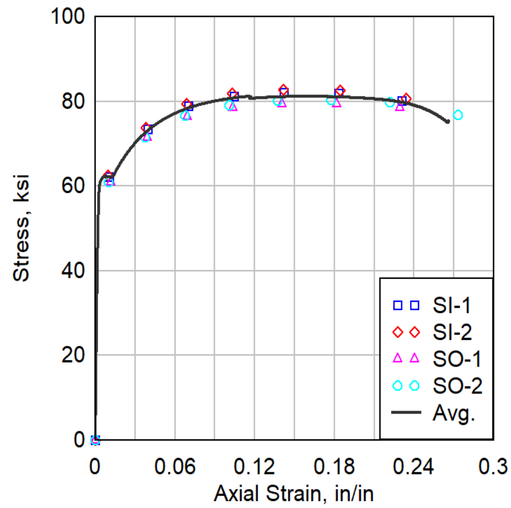



Figure 106: 30USW57 Small Face

35USC35

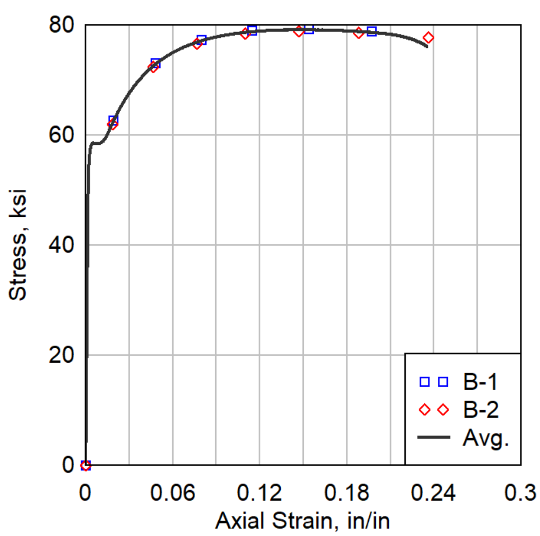



Figure 107: 35USC35 Large Face

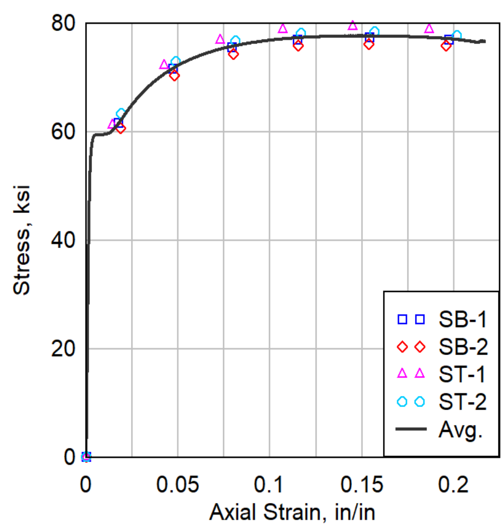



Figure 108: 35USC35 Small Face

35USC57

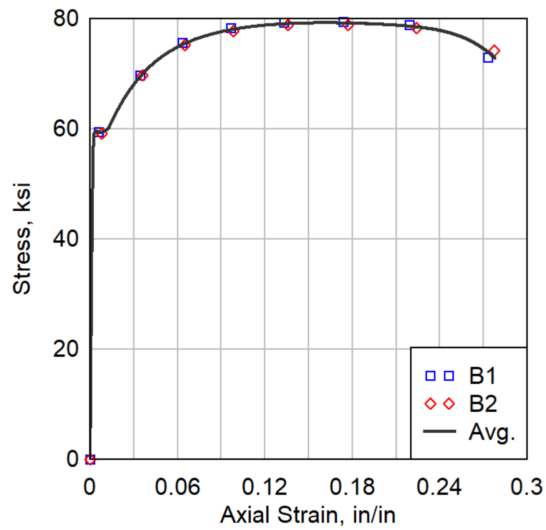



Figure 109: 35USC57 Large Face

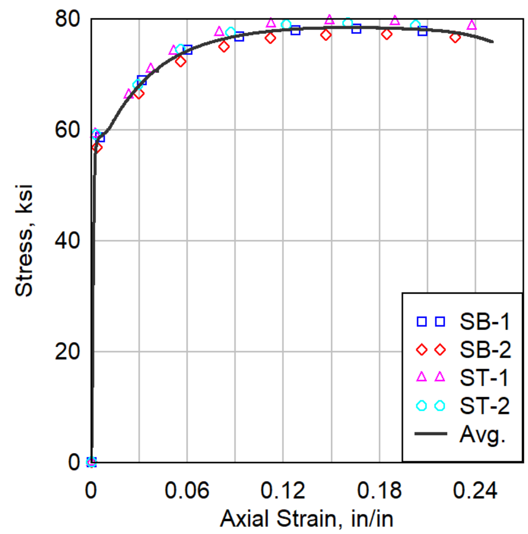



Figure 110: 35USC57 Small Face

35USC46

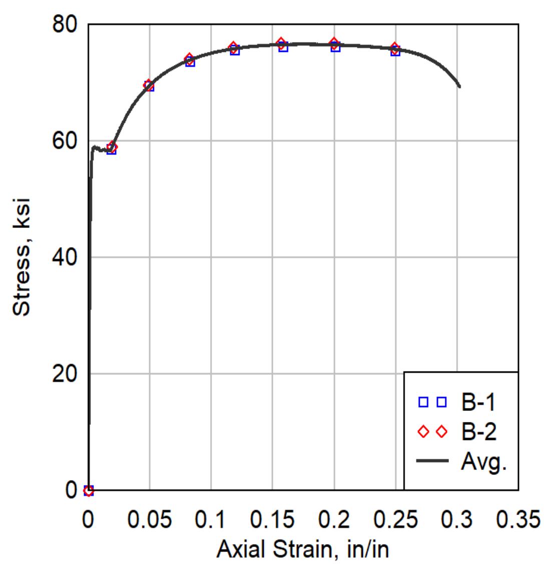



Figure 111: 35USC46 Large Face

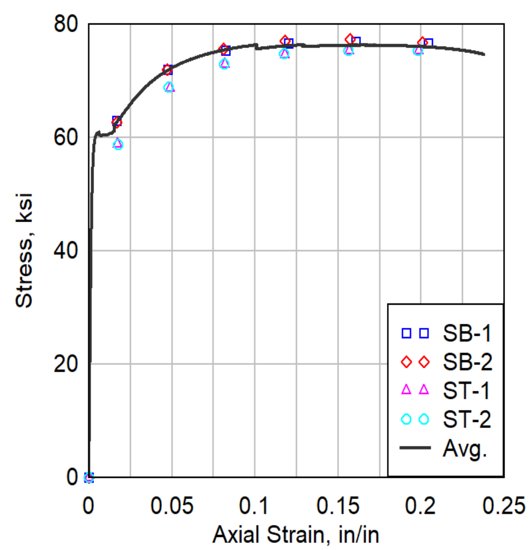



Figure 112: 35USC46 Small Face

25USC35

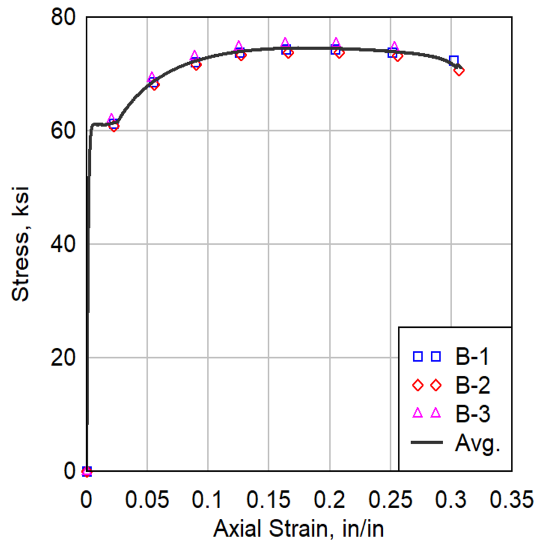



Figure 113: 25USC35 Large Face

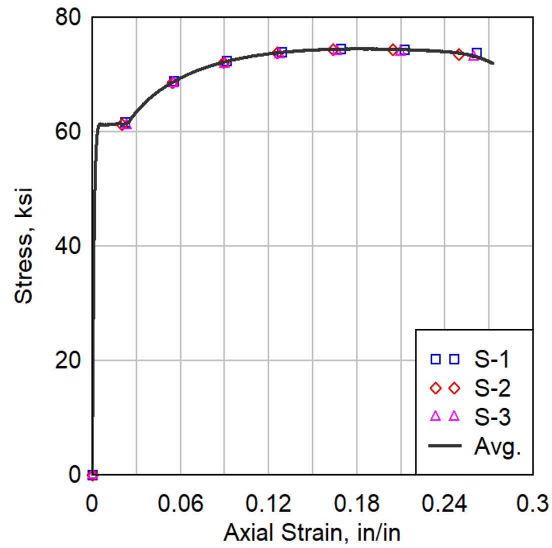



Figure 114: 25USC35 Small Face

35USD35

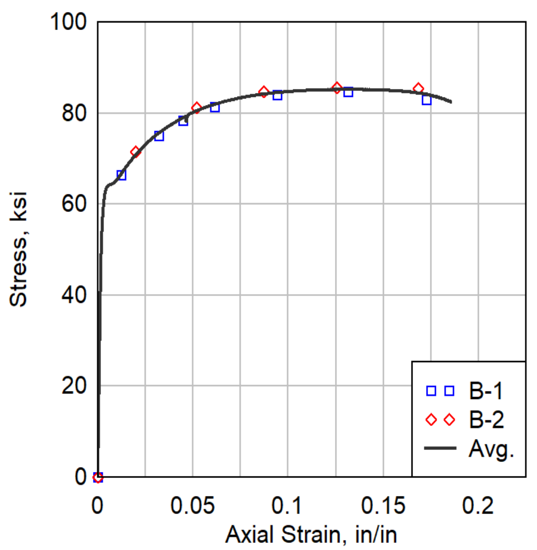



Figure 115: 35USD35 Large Face

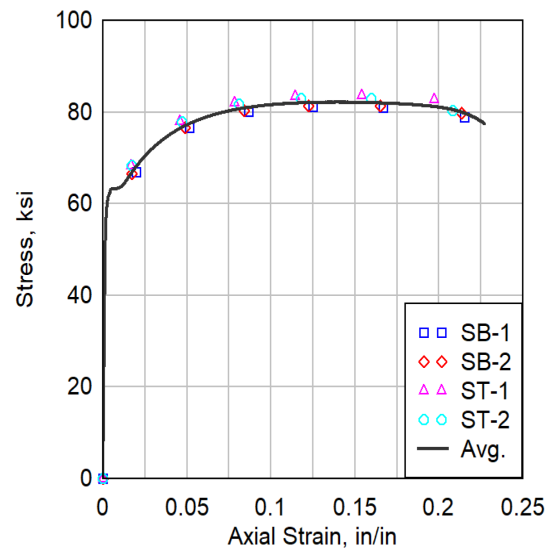



Figure 116: 35USD35 Small Face

35USD57

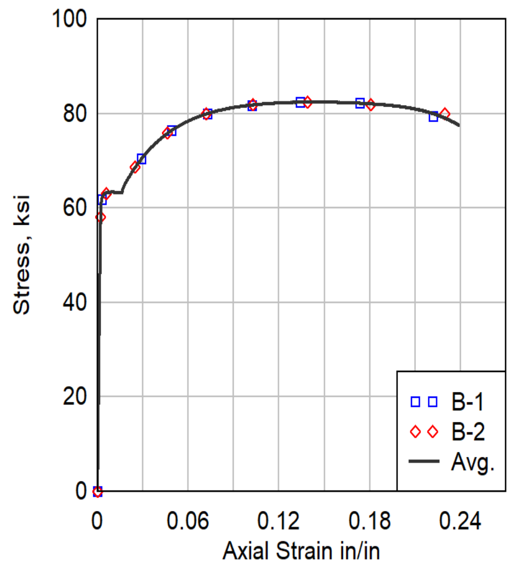



Figure 117: 35USD57 Large Face

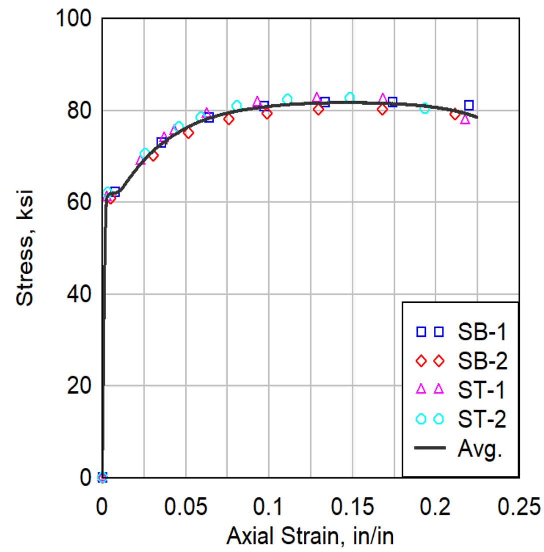



Figure 118: 35USD57 Small Face

35USD46

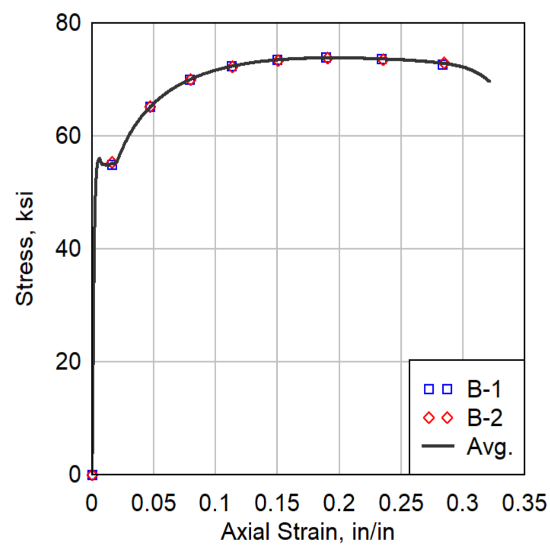



Figure 119: 35USD46 Large Face

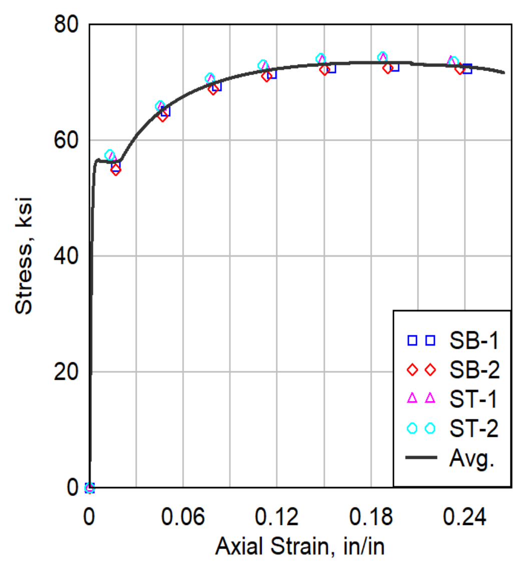



Figure 120: 35USD46 Small Face

# Appendix C – Aiges Connection Test Results

057-30USW35

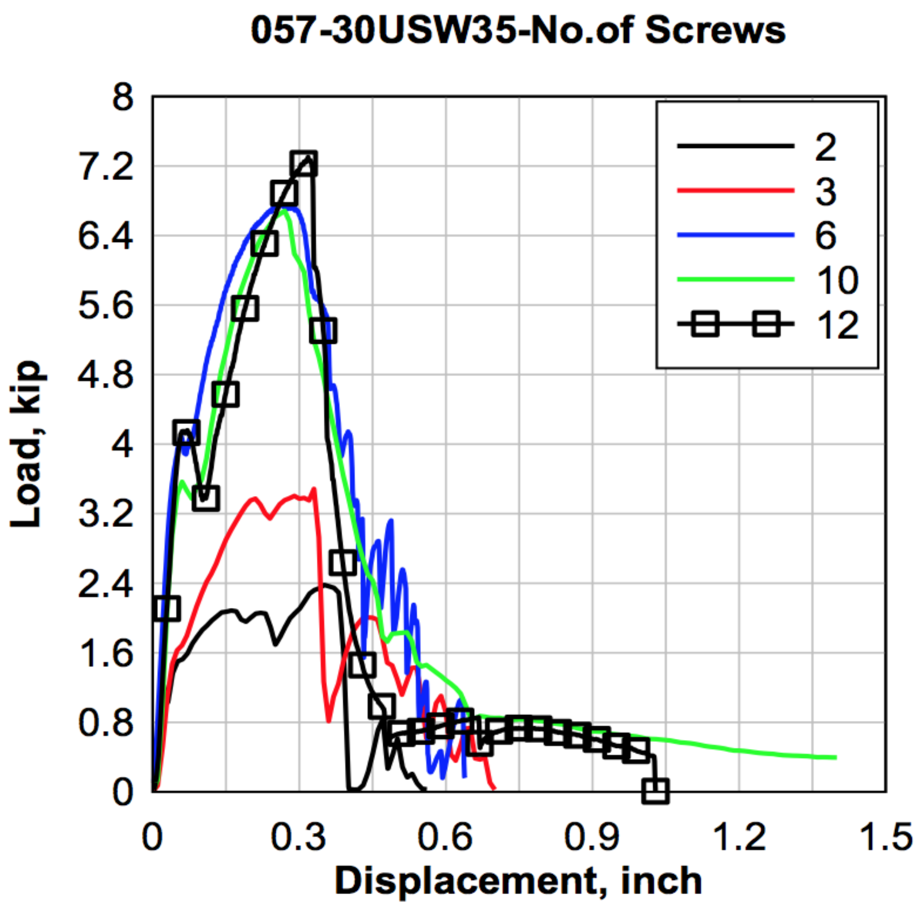



Figure 121: 057-30USW35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 057-30USW35-2 | 62.77 |
| 057-30USW35-3 | 39.57 |
| 057-30USW35-6 | 95.11 |
| 057-30USW35-10 | 76.30 |
| 057-30USW35-12 | 82.76 |

Table 18: 057-30USW35 Stiffness

046-30USW46

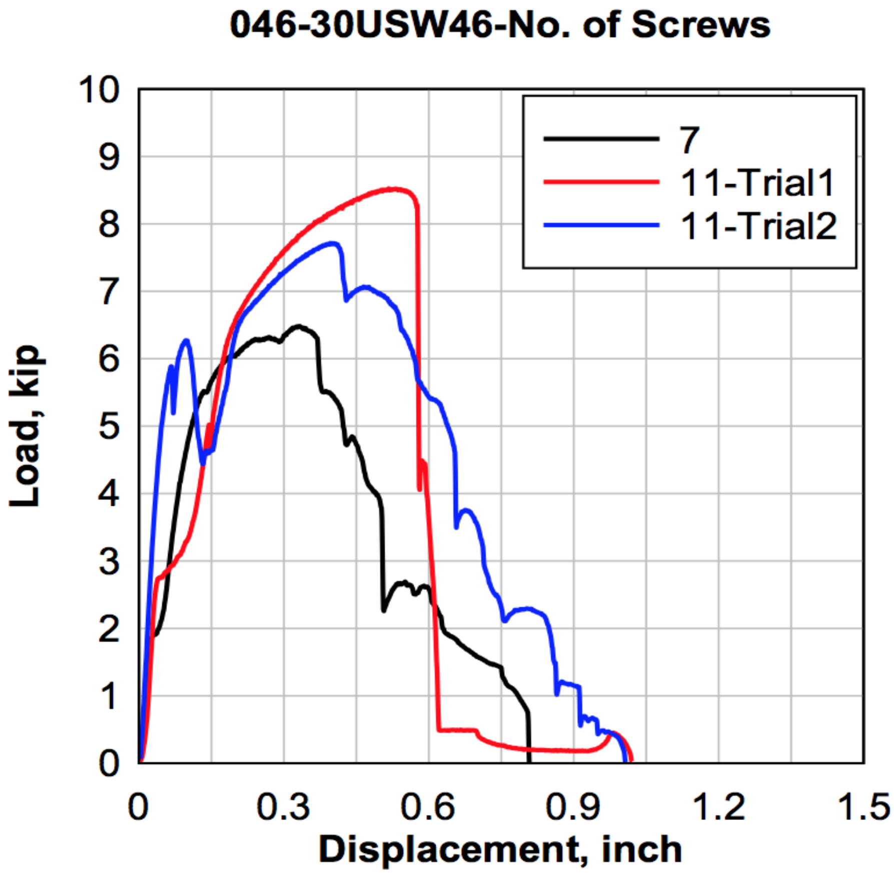



Figure 122: 046-30USW46 Results

| Sample | Stiffness (kip/in) |
| --- | --- |
| 046-30USW46-7 | 76.01 |
| 046-30USW46-11 Trial 1 | 83.49 |
| 046-30USW46-11 Trial 2 | 116.60 |

Table 19: 046-30USW46 Stiffness

057-30USW46

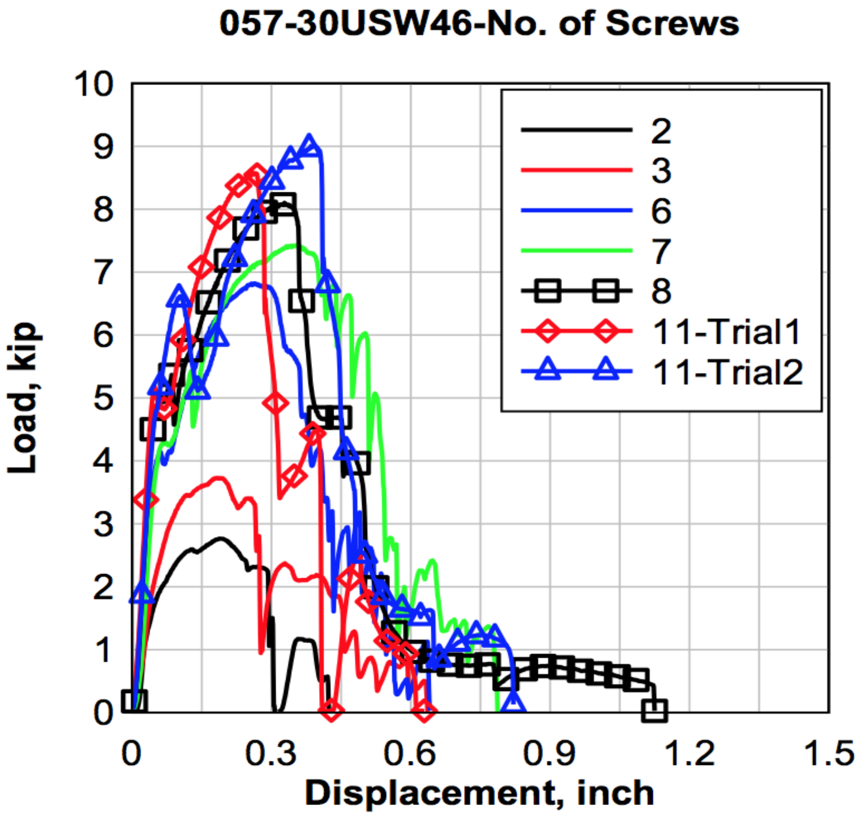



Figure 123: 057-30USW46 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 057-30USW46-2 | 39.54 |
| 057-30USW46-3 | 41.02 |
| 057-30USW46-6 | 82.62 |
| 057-30USW46-7 | 85.29 |
| 057-30USW46-8 | 108.43 |
| 057-30USW46-11 Trial 1 | 124.35 |
| 057-30USW46-11 Trial 2 | 108.35 |

Table 20: 057-30USW46 Stiffness

046-30USW35

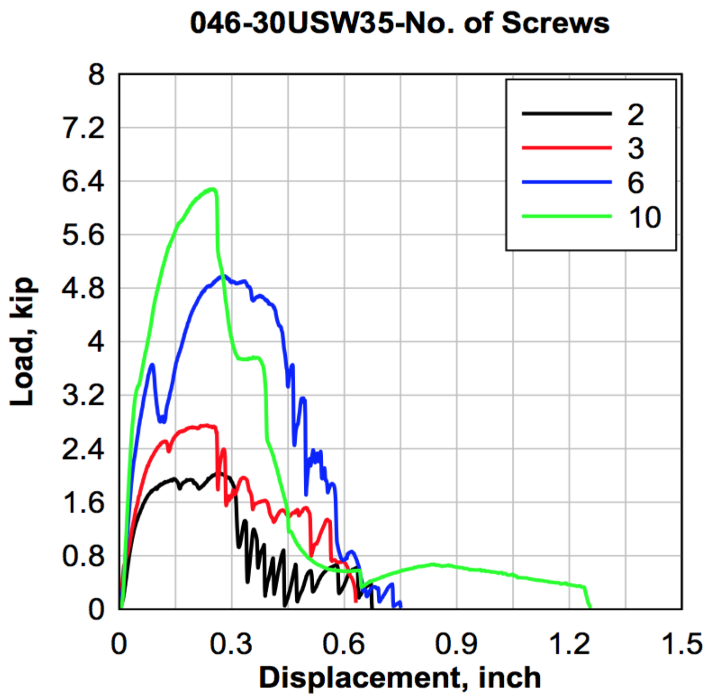



Figure 124: 046-30USW35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 046-30USW35-2 | 27.09 |
| 046-30USW35-3 | 27.53 |
| 046-30USW35-6 | 47.30 |
| 046-30USW35-10 | 82.64 |

Table 21: 046-30USW35 Stiffness

035-30USW57

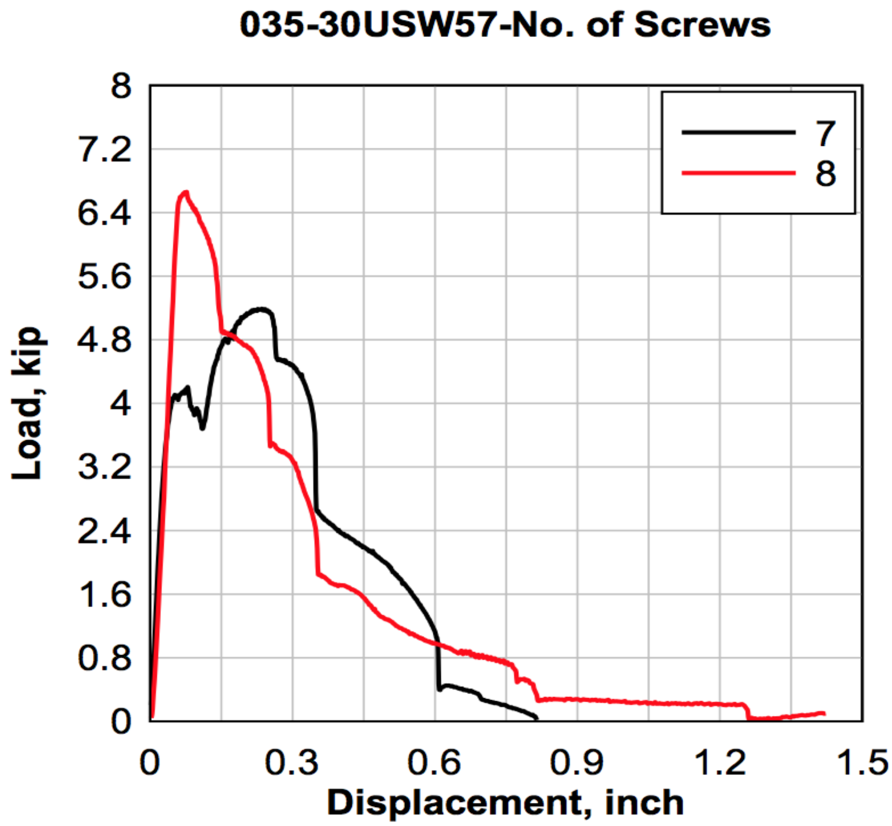



Figure 125: 035-30USW57 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 035-30USW57-7 | 105.51 |
| 035-30USW57-8 | 119.75 |

Table 22: 035-30USW57 Stiffness

035-362USWD35

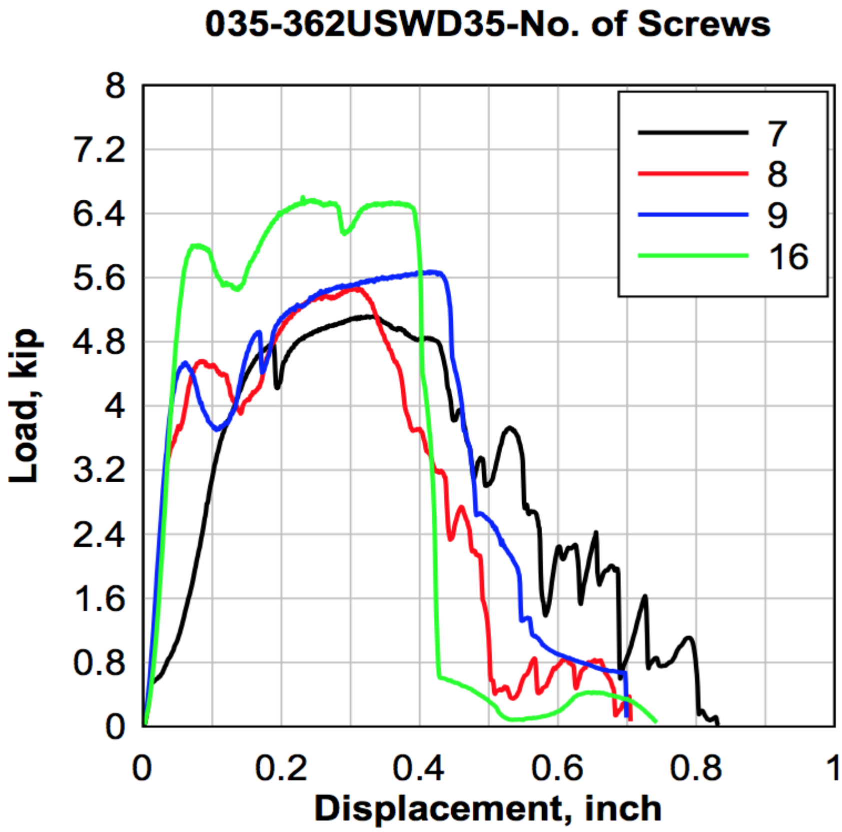



Figure 126: 035-362USWD35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 035-362USWD35-7 | 53.25 |
| 035-362USWD35-8 | 103.05 |
| 035-362USWD35-9 | 105.34 |
| 035-362USWD35-16 | 109.47 |

Table 23: 035-362USWD35 Stiffness

035-25USWD35

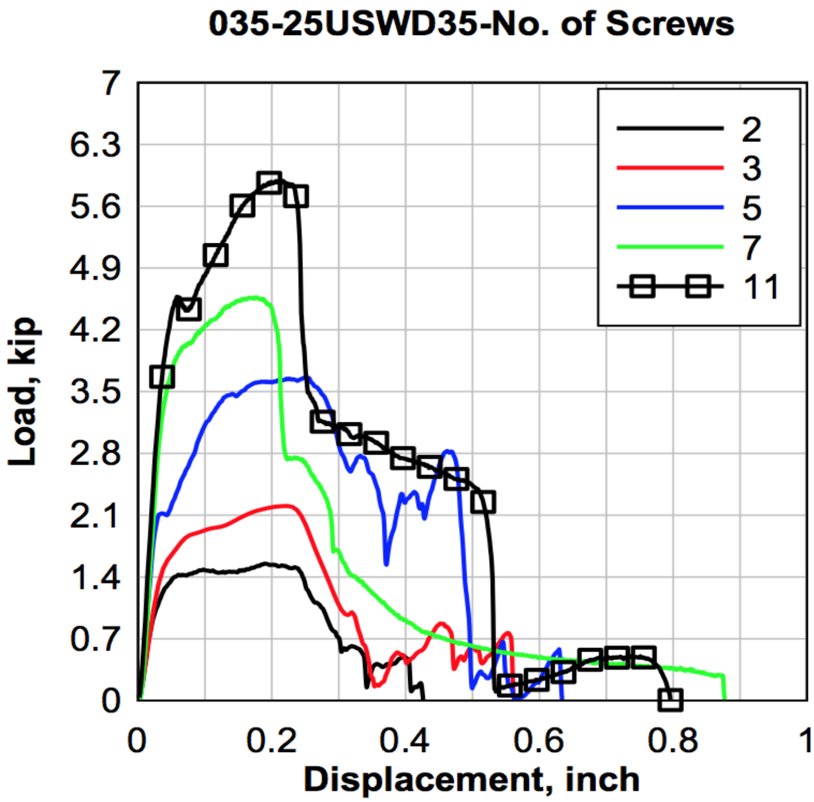



Figure 127: 035-25USWD35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 035-25USWD35-2 | 35.07 |
| 035-25USWD35-3 | 42.26 |
| 035-25USWD35-5 | 84.85 |
| 035-25USWD35-7 | 95.03 |
| 035-25USWD35-11 | 113.24 |

Table 24: 035-25USWD35 Stiffness

046-25USWD35

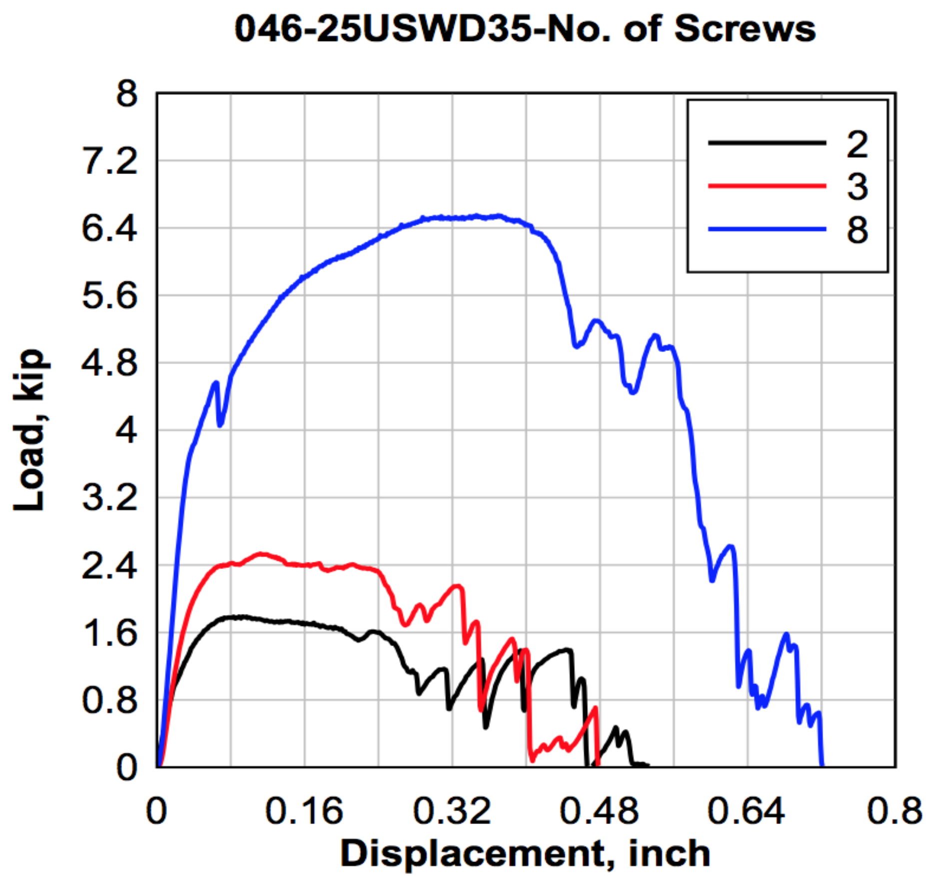



Figure 128: 046-25USWD35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 046-25USWD35-2 | 37.076 |
| 046-25USWD35-3 | 51.221 |
| 046-25USWD35-8 | 113.764 |

Table 25: 046-25USWD35 Stiffness

057-25USWD35

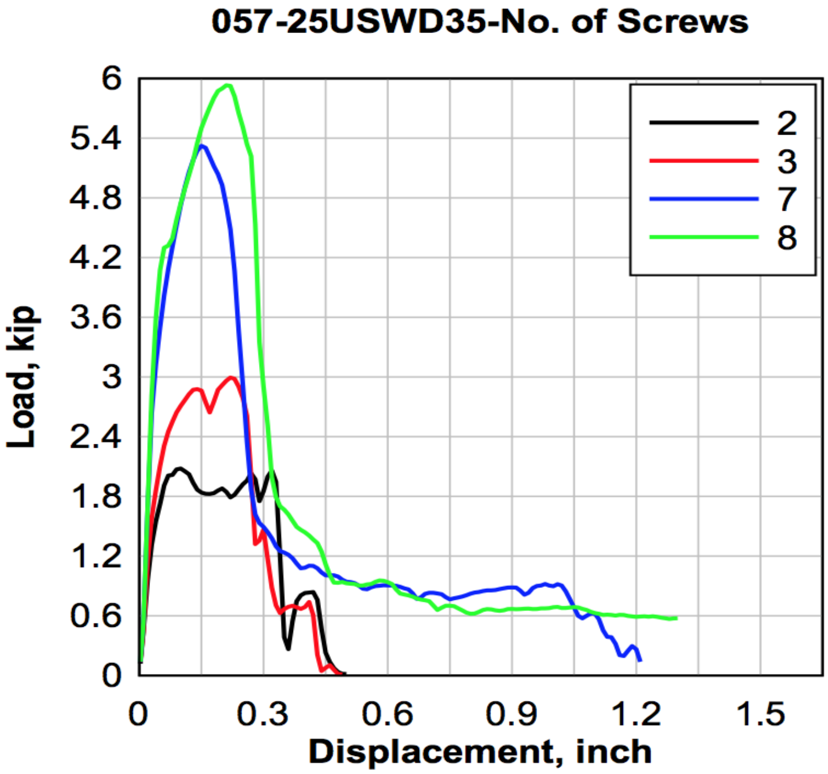



Figure 129: 057-25USWD35 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 057-25USWD35-2 | 31.71 |
| 057-25USWD35-3 | 35.05 |
| 057-25USWD35-7 | 83.75 |
| 057-25USWD35-8 | 87.62 |

Table 26: 057-25USWD35 Stiffness

057-362USWD57

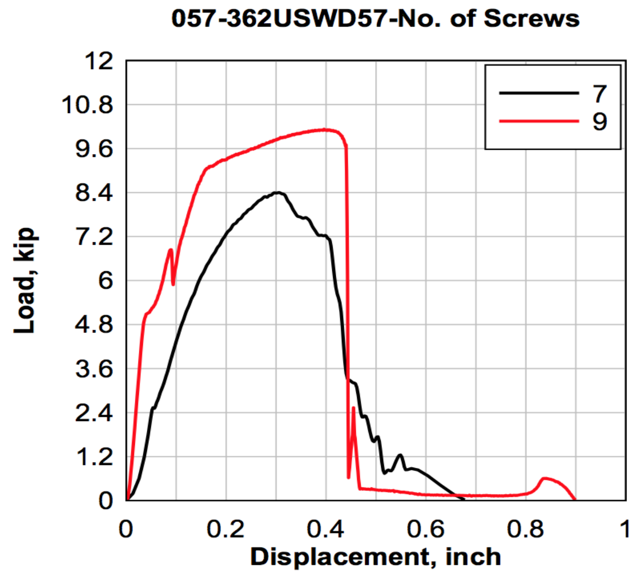



Figure 130: 057-362USWD57 Results

| Sample | Stiffness (kip/in) |
| --- | --- |
| 057-362USWD57-7 | 49.35 |
| 057-362USWD57-9 | 150.84 |

Table 27: 057-362USWD57 Stiffness

## Other Results

035-30USW46-10

| Sample | Stiffness (kip/in) |
| --- | --- |
| 035-30USW46-10 | 54.95 |

Table 28: 035-30USWD46-10 Stiffness

035-362USWD46-8

| Sample | Stiffness (kip/in) |
| --- | --- |
| 035-362USWD46-8 | 78.09 |

Table 29: 035-362USWD46-8 Stiffness

# Appendix D – TrusSteel Connection Test Results

028-33W75x75

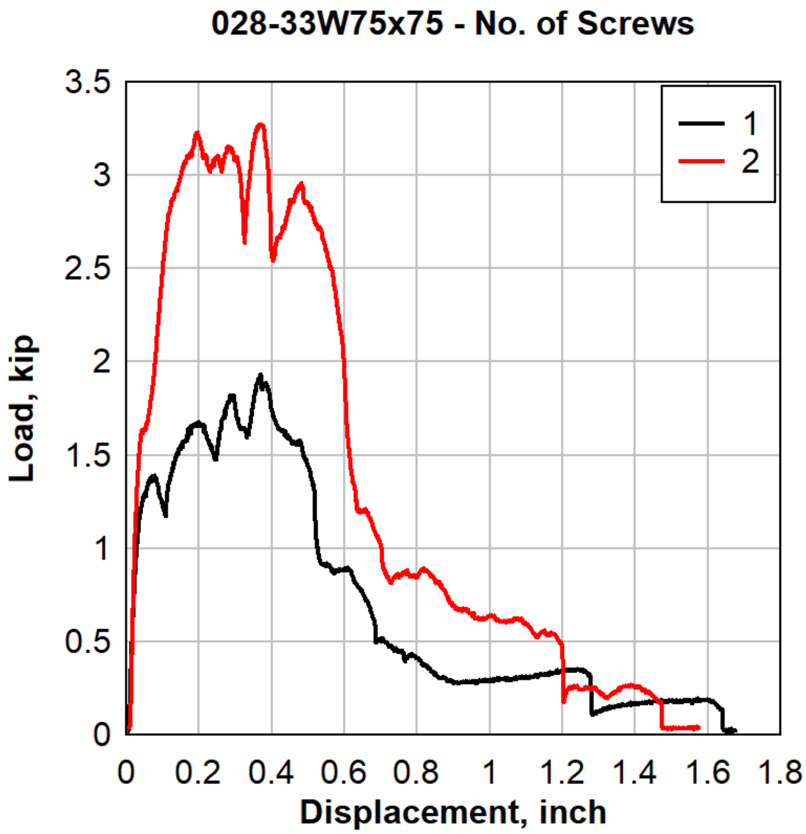



Figure 131: 028-33W75x75 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 028-33W75x75-1 | 47.91 |
| 028-33W75x75-2 | 82.92 |

Table 30: 028-33W75x75 Stiffness

028-33W75x150

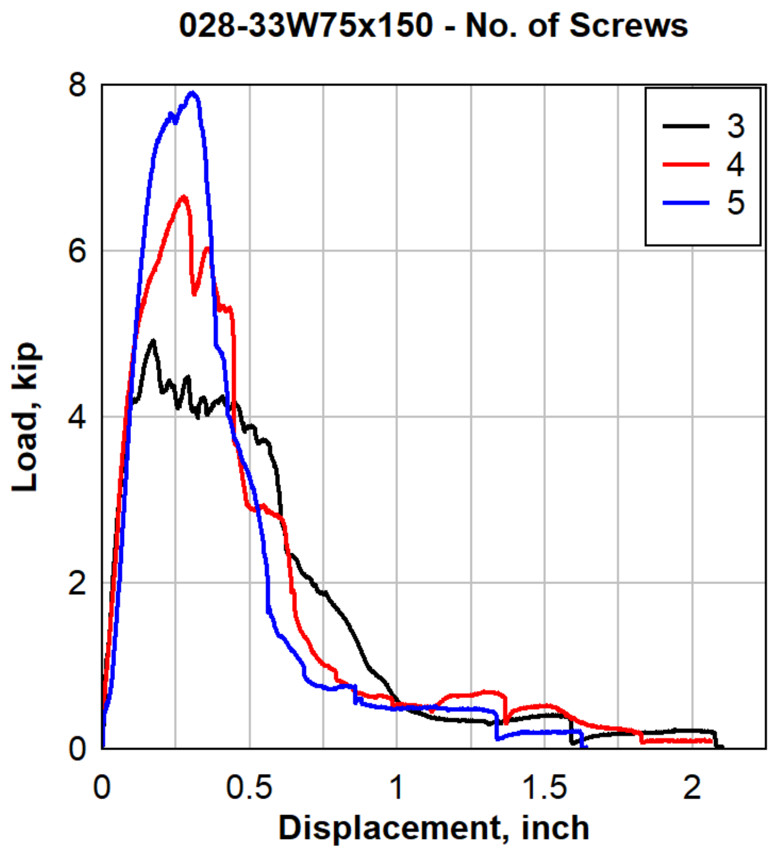



Figure 132: 028-33W75x150 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 028-33W75x150-3 | 42.48 |
| 028-33W75x150-4 | 47.29 |
| 028-33W75x150-5 | 54.44 |

Table 31: 028-33W75x150 Stiffness

028-33W75x225

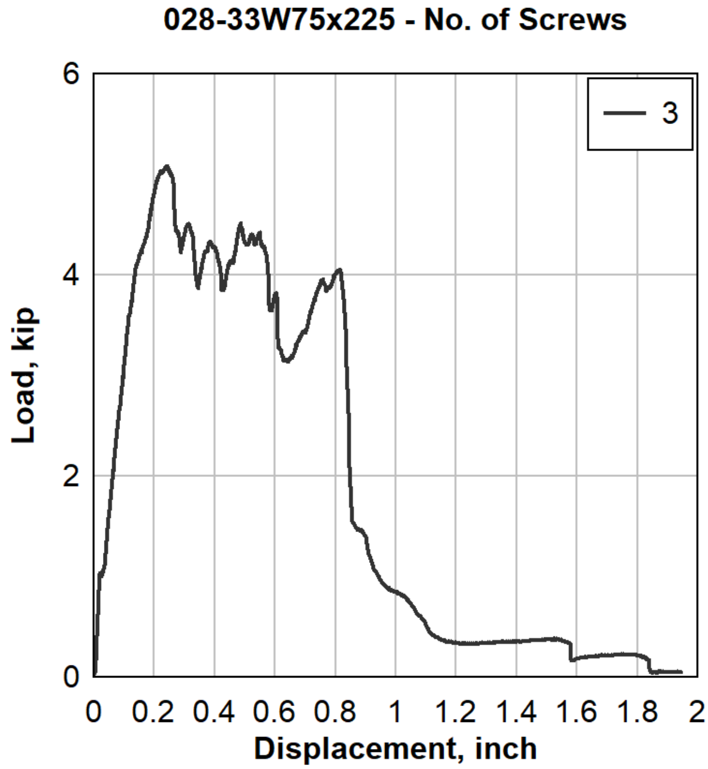



Figure 133: 028-33W75x225 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 028-33W75x225-3 | 29.44 |

Table 32: 028-33W75x225 Stiffness

033-33W75x150

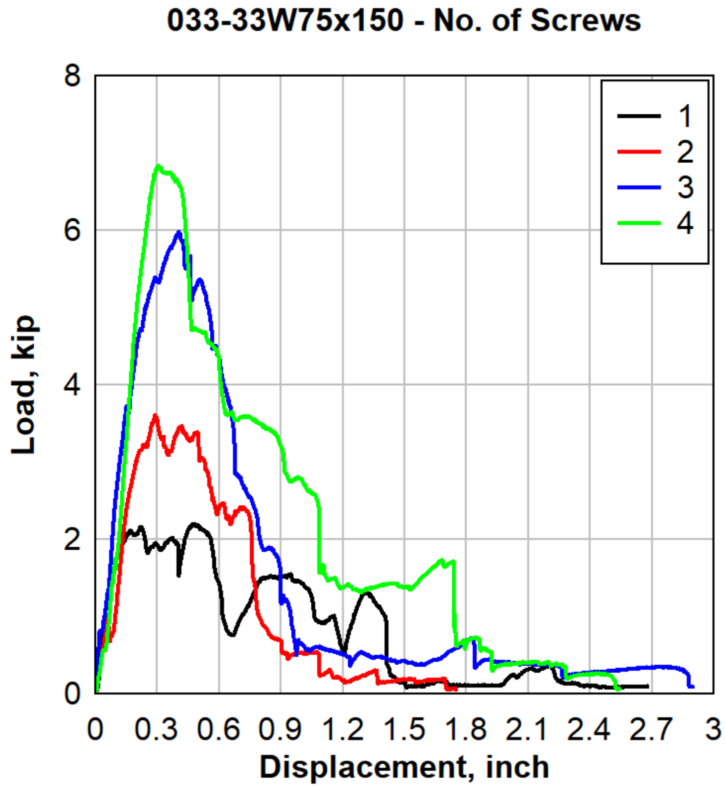



Figure 134: 033-33W75x150 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 033-33W75x150-1 | 12.61 |
| 033-33W75x150-2 | 15.04 |
| 033-33W75x150-3 | 21.94 |
| 033-33W75x150-4 | 35.22 |

Table 33: 033-33W75x150 Stiffness

043-33W75x75

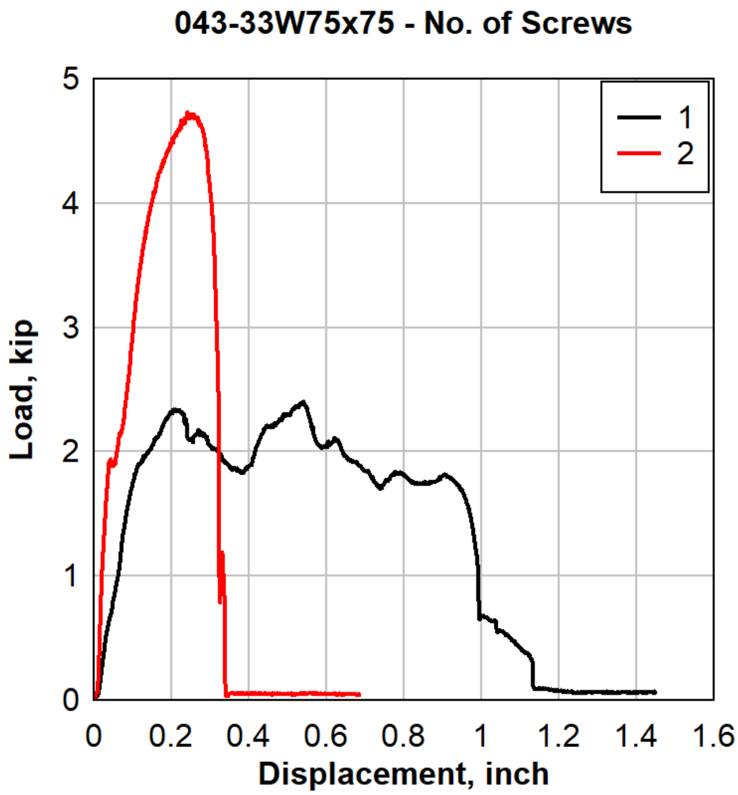



Figure 135: 043-33W75x75 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 043-33W75x75-1 | 18.95 |
| 043-33W75x75-2 | 31.25 |

Table 34: 043-33W75x75 Stiffness

043-33W75x150

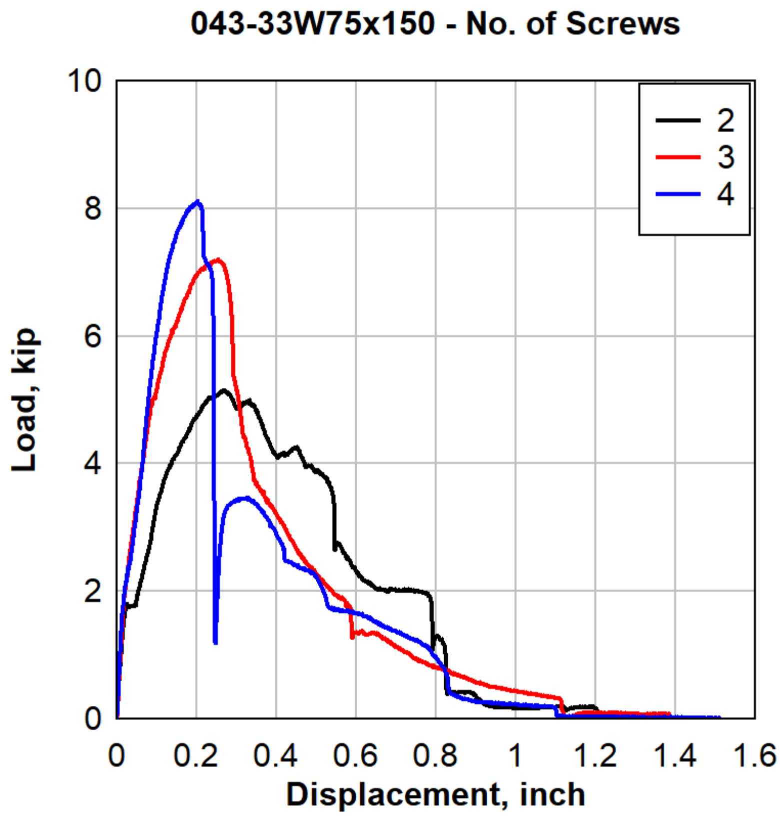



Figure 136: 043-33W75x150 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 043-33W75x150-2 | 27.85 |
| 043-33W75x150-3 | 35.31 |
| 043-33W75x150-4 | 52.70 |

Table 35: 043-33W75x150 Stiffness

043-33W75x225

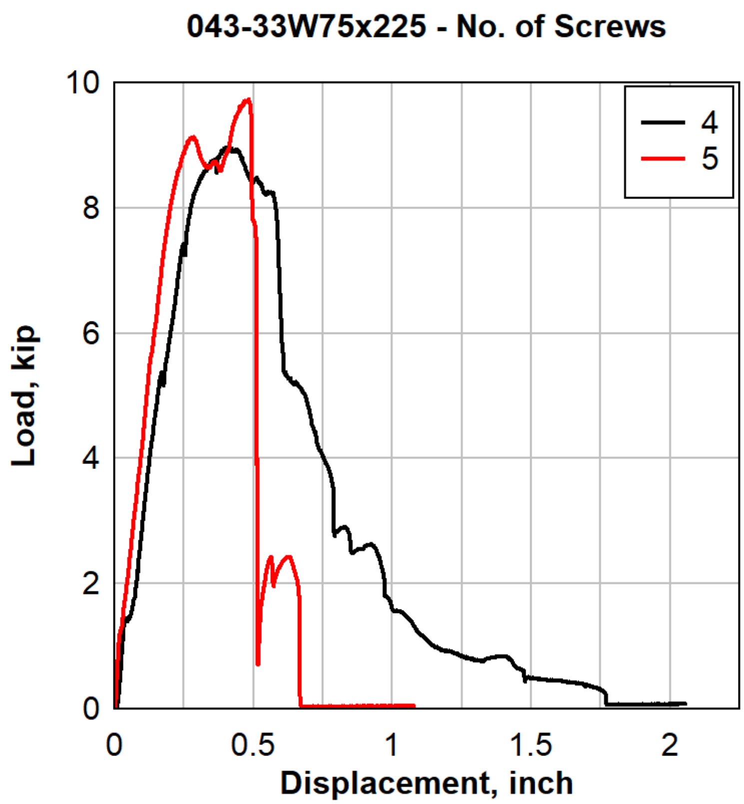



Figure 137: 043-33W75x225 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 043-33W75x225-4 | 30.84 |
| 043-33W75x225-5 | 38.69 |

Table 36: 043-33W75x225 Stiffness

054-33W75x150

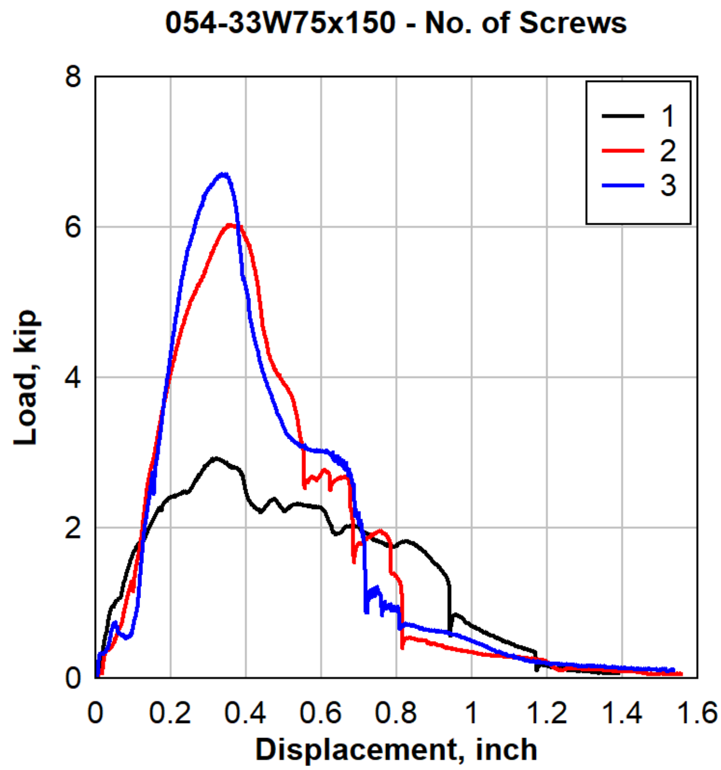



Figure 138: 054-33W75x150 Results

| Sample | Stiffness (kip/in) |
|---|---|
| 054-33W75x150-1 | 10.44 |
| 054-33W75x150-2 | 23.71 |
| 054-33W75x150-3 | 32.07 |

Table 37: 054-33W75x150 Stiffness

054-33W150x150

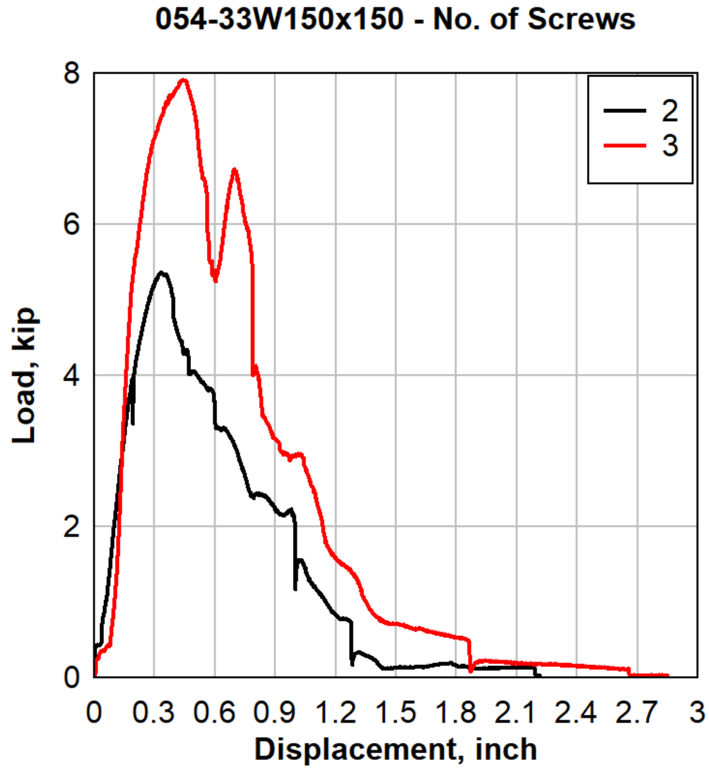



Figure 139: 054-33W150x150 Results

| Sample | Stiffness (kip/in) |
| --- | --- |
| 054-33W150x150-2 | 22.15 |
| 054-33W150x150-3 | 26.45 |

Table 38: 054-33W150x150 Stiffness

# Appendix E – End Bearing Connection Test Results

046-W046-7

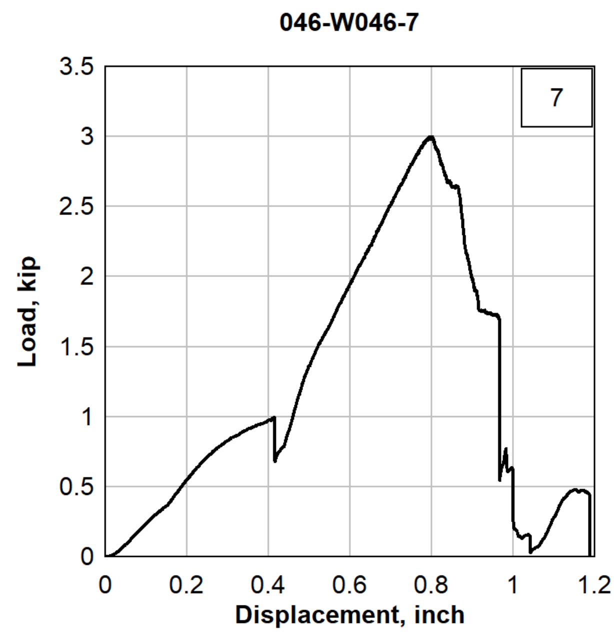



Figure 140: 046-W046-7 Results

035-WD035

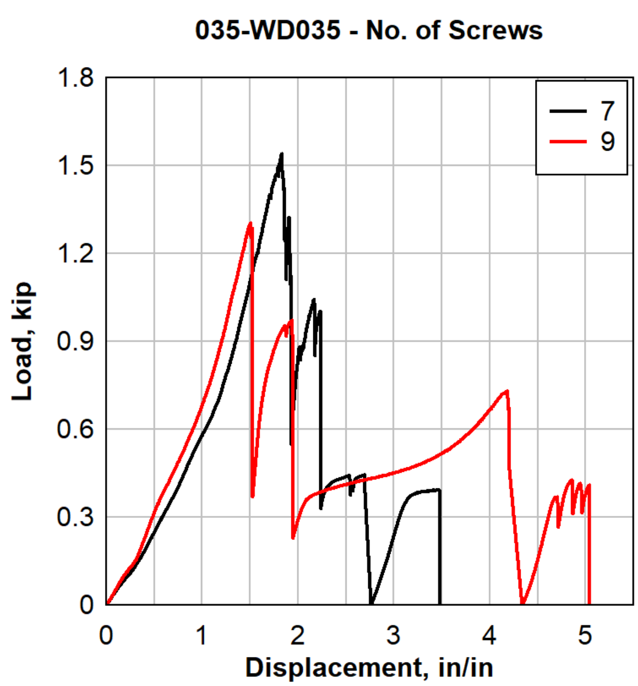



Figure 141: 035-WD035 Results

035-WD046-10

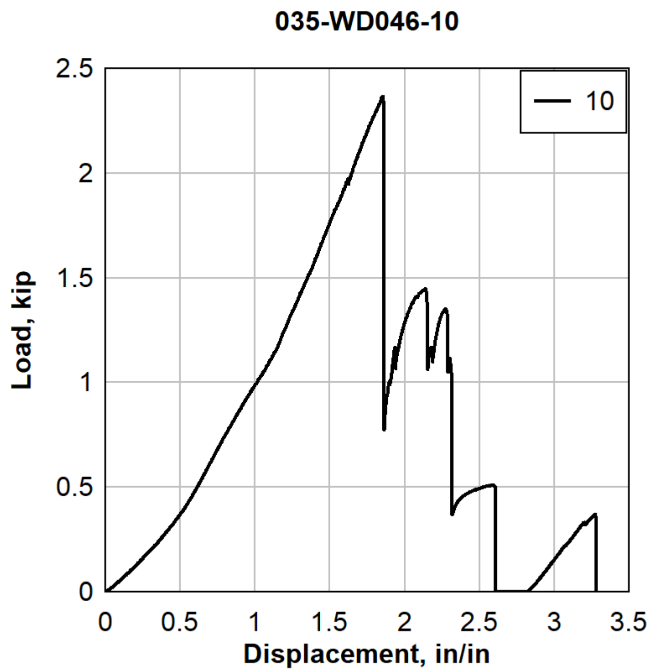



Figure 142: 035-WD046-10 Results

046-WD046-10

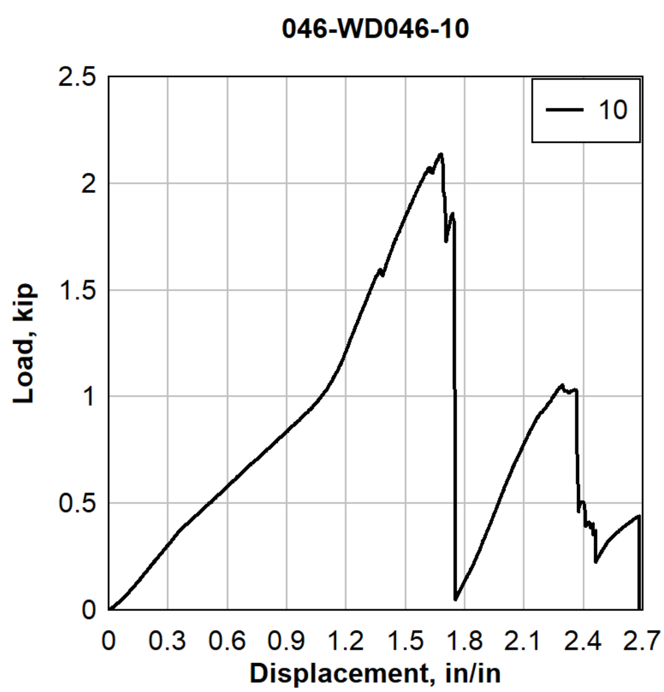



Figure 143: 046-WD046-10 Results