Evaluation of the Ability of Adhesives to Substitute Nails in Wooden Block Pallets

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ABSTRACT

The most common fastening technique that is used to connect the components of wooden pallets together are helically or annularly threaded pallet nails. Pallet nails create a strong durable connection and increase manufacturing efficiency for a low cost. However, nails can also cause iron staining, wood splitting, and when exposed can cause product damage or personnel injury. Using adhesives could be a solution to these problems, but only if the adhesives’ strength and durability is comparable or higher than nails. The objective of the study was to investigate the tensile and shear strength of pallet connections secured using commercially available wood adhesives and compare their performance to pallet connections secured using common pallet nails.

The lowest pre-compression pressure resulted in the best tension and shear performance for a solvent based construction adhesive (SBCA). The pre-compression pressure did not have any practical effect on the performance of the two-part emulsion polymer isocyanate (EPI) adhesive. Samples made with the solvent based construction adhesive (SBCA) had greater strength and energy at failure than nailed samples. Meanwhile, the samples made with the two-part emulsion polymer isocyanate (EPI) adhesive had equal or greater strength than nailed samples, except for during the tension parallel to the grain tests in which they had equal or lower strength.

GENERAL AUDIENCE ABSTRACT

The most common technique used to connect the components of wooden pallets together is nails. Pallet nails create a strong connection with high manufacturing efficiency for a low cost. However, nails can cause iron staining, wood splitting, and when exposed can cause product damage or personnel injury. Using adhesives could be a solution to these problems, but only if the adhesives' strength and durability is comparable or higher than nails. The objective of this study was to investigate the tensile and shear strength of pallet connections when secured using commercially available wood adhesives and compare its performance to pallet connections secured by using common pallet nails.

The lowest pre-compression pressure tested resulted in the best overall performance for a solvent based construction adhesive (SBCA); meanwhile, pre-compression pressure did not have any practical effect on the performance of the two-part emulsion polymer isocyanate (EPI) adhesive tested. Therefore, using a lower pre-compression pressure would provide adequate performance and could also improve the ease of manufacturing and potentially reduce overall costs.

Based on the tests conducted it was found that the solvent based construction adhesive (SBCA) demonstrated the best performance of all connection methods and could be a potential replacement for nails. More tests, such as weathering and impact, should be conducted to determine the full limitations of the adhesive in use.

For my mother
who was there for it all,
and for my father
who watched from above

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1 Literature Review

1.1 Wood Pallets

Pallets are rigid horizontal platforms designed to be used in a distribution environment for handling goods. This handling includes stacking, storing, and transporting (MH1 Committee, 2005). There are over approximately 2 billion pallets in use in the United States of which approximately 95% are made of wood (White & Hamner, 2005). Pallets have been used in multiple industries, including food and beverage, building materials, chemical, breweries, oil refinery, meatpacking, and steel fabricators since the 1930's (Eichler, 1976).

1.1.1 Classifications

Pallets are described and classified based on their class, usage, entry, style, and design. When categorized by use pallets can be single-use, also called expendable or nonreturnable, reusable, or special purpose. Single-use pallets are designed to be able to withstand only one trip. Reusable pallets are designed to be used for multiple trips and/or for various types of unit loads for shipping and handling (NWPCA, 2014). Lastly, there are special purpose pallets, which the US Department of Agriculture's Forest Products Laboratory (U.S.D.A. Forest Service, 1971) describes as pallets with features tailored to protect a specific product or unit load.

There are two classes of wooden pallets, stringer and block. Stringer pallets are supported by multiple stringers, longitudinal beams that support the deckboards. Block pallets are supported by blocks, which are rectangular or square deck spacers that support the stringerboards and deckboards (NWPCA, 2014). Wooden pallets are composed of multiple components, including deck boards, stringerboards, and, depending on the pallet class, either stringers or blocks. Below are two schematics describing all components which make up stringer and block pallets (**Figure 1** and **Figure 2**) taken from the Approved American National Standard MH1 (MH1 Committee, 2005).

Types of pallets include flush, single wing, and double wing. Flush pallets have deckboards that have their outer edges aligned with either the stringers or stringerboards. If the deckboards extend past the stringers or stringerboards then they are classified as winged. If this extension is only on the top deckboards but the bottom deck is flush, then it is a single wing pallet. If both the bottom and top decks extend past the stringers or stringerboards then it is a double wing pallet (U.S.D.A. Forest Service, 1971). Pallets are often winged when they are in a distribution system where they need to be supported by slings, or when the designer would like to increase the stiffness of the pallet by reducing the span between the stringers.

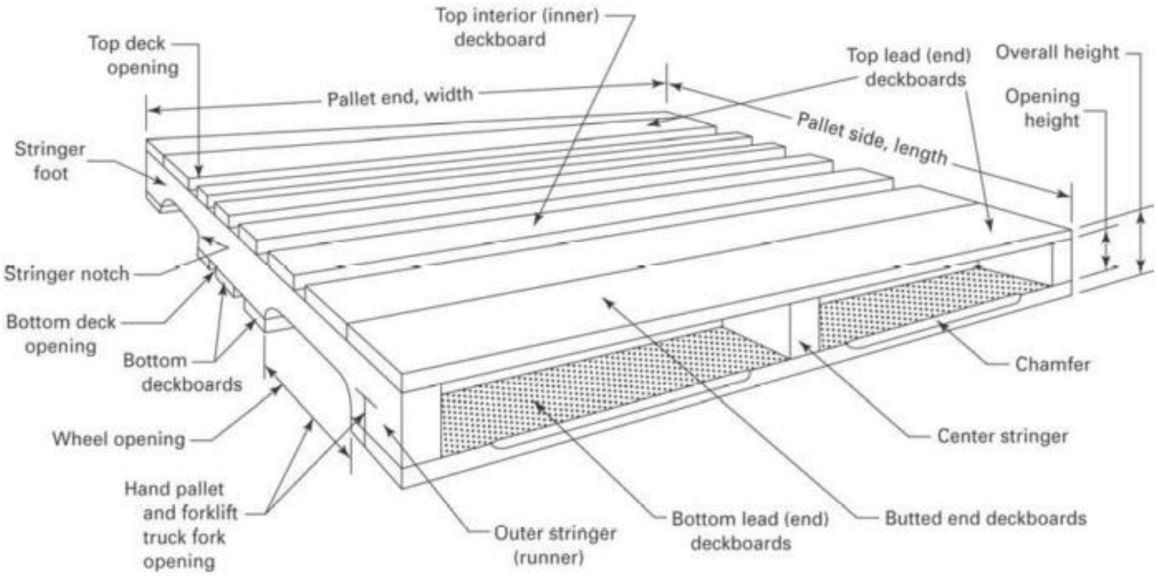


Figure 1. Schematic of a partial four-way entry, double face, nonreversible, flush stringer design pallet from the Approved American National Standard MH1 (MH1 Committee, 2005)

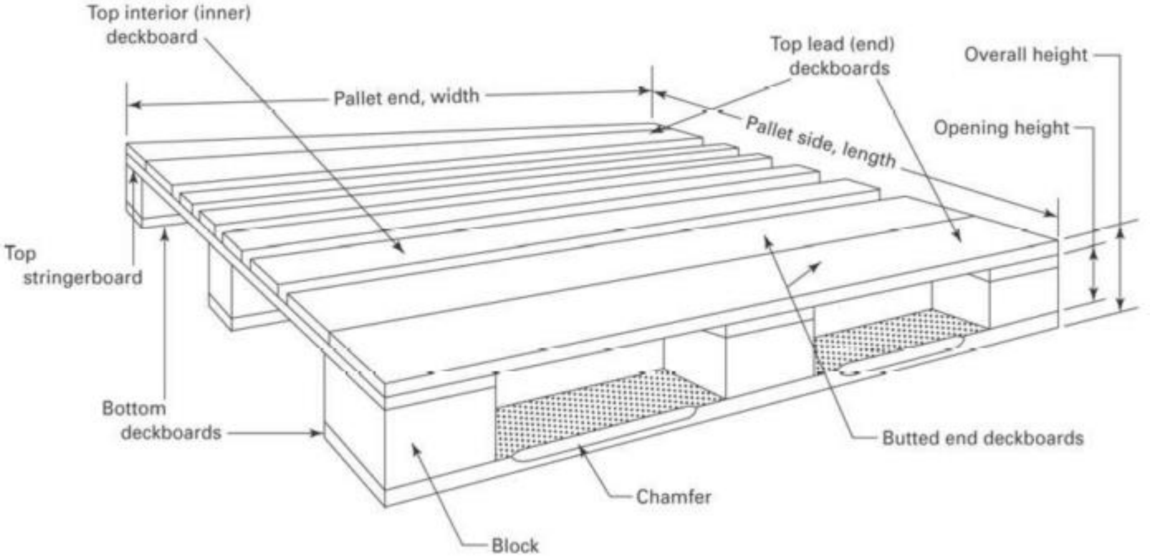


Figure 2. Schematic of a full four-way entry, double face, nonreversible, flush block design pallet from the Approved American National Standard MH1 (MH1 Committee, 2005)

The style of the pallet is dependent on whether it has a bottom deck. Pallets without bottom decks, also known as single-face style pallets, are often referred to as skids, especially if they have only 2 stringers. Most pallets are double-faced pallets, meaning they have a bottom deck and a top deck. If a pallet is double-faced with both faces being identical to each other, then it is considered a reversible pallet (U.S.D.A. Forest Service, 1971). There are also different ways that the bottom deck can be assembled onto the pallet. The bottom deck can be unidirectional, overlapping, perimeter, and cruciform. Unidirectional pallets have all bottom deckboards oriented in the same direction. Overlapping bottom decks have bottom deck boards as well as perpendicular bottom stringerboards. Perimeter bottom decks have bottom deckboards that span along lengths and widths of the pallet along the edges, as well as across the center (**Figure 3**).

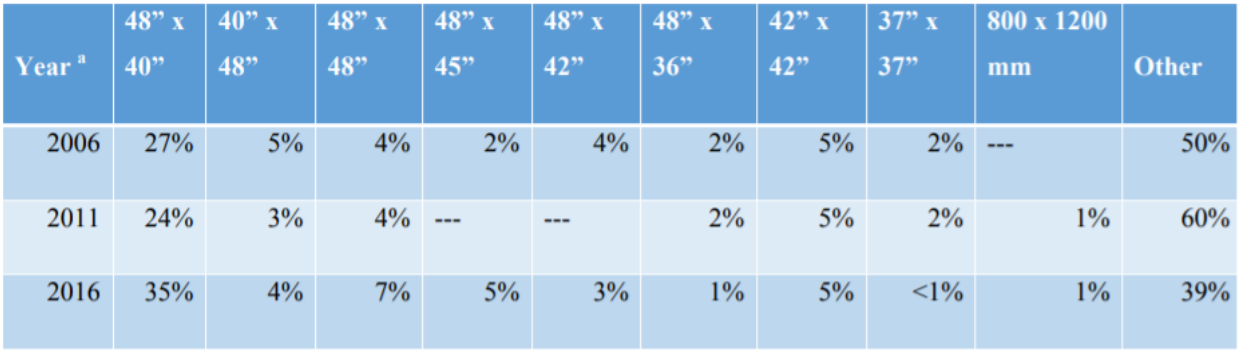
Figure 3. photographs of a unidirectional block pallet (left), unidirectional notched stringer pallet (middle), and perimeter block pallet (right)

Pallets can also be categorized based on their accessibility to handling equipment, such as forklifts and pallet jacks. Based on their accessibility pallets can have two-way, partial four-way, and four-way entry. Two-way pallets are typically unnotched stringer pallets and can be entered with either forklifts or pallet jacks. Partial four-way pallets are pallets with limited access on two sides; the most common partial four-way is the notched stringer pallet. This limited access is due to the difference in the heights of pallet jacks and thickness of forklift tines. Four-way pallets can be entered on all sides, and they are not limited to any certain type of handling equipment; these are typically block pallets (NWPCA, 2014). See **Figure 4** below to see the different entry categories for pallets.

Figure 4. Photographs of two-way entry stringer pallet (top), partial four-way entry stringer pallet (bottom left), and four-way entry block pallet (bottom right)

1.1.2 Sizes

The length and width of a wooden pallet are based on components rather than comparative dimensions. The longest side of a pallet it not necessarily its length. The length of the pallet is equivalent to the length of the stringers, or runners, in stringer pallets or to the stringerboards in block pallets. The width is equivalent to the length of the top deckboards in both stringer and block pallets (NWPCA, 2014). The first dimension listed for a pallet is the length, or the length of the stringers, and the second dimension listed is the width and is the length of the top deckboards. For example, a 48 in. x 40 in. stringer pallet is one that has 48 in. long stringers and 40 in. long deckboards. If the pallet were 40 in. x 48 in., then it would have 40 in. long stringers and 48 in. long top deckboards. In the United States, pallet sizes are not standardized and vary by the industry in which they are used. There are many special purpose pallets in the United States that have a wide range of dimensions. A study was conducted at Virginia Tech (Gerber, 2018) to quantify the frequency of pallet sizes used in the United States. The distribution of the pallet sizes found by Gerber is presented in **Table 1**. The most common size was 48 in. x 40 in. pallets; these made up 35% of new pallets manufactured in 2016.

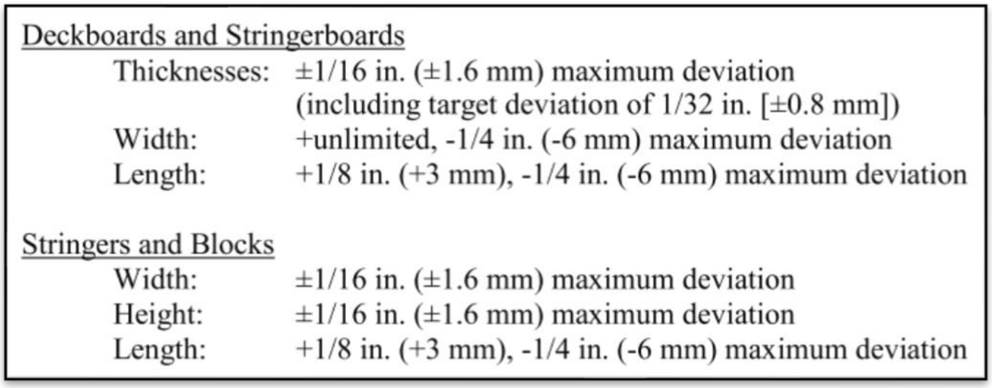


Year ª	48" x 40"	40" x 48"	48" x 48"	48" x 45"	48" x 42"	48" x 36"	42" x 42"	37" x 37"	800 x 1200 mm	Other
2006	27%	5%	4%	2%	4%	2%	5%	2%	---	50%
2011	24%	3%	4%	---	---	2%	5%	2%	1%	60%
2016	35%	4%	7%	5%	3%	1%	5%	<1%	1%	39%

Table 1. New Wood Pallets Produced by Responding Firms by Size: 2006-2016 (Gerber, 2018)

1.1.3 Manufacturing

There are various methods of manufacturing pallets, depending on whether the pallets are newly manufactured, repaired, or remanufactured. Newly manufactured pallets are built with all new parts and can be classified as single use, reusable, or special use pallets. The NWPCA Uniform Standard for Wooden Pallets (NWPCA, 2014) gives dimension tolerances based on Good Manufacturing Practices (GMP) for deckboards, stringerboards, stringers, and blocks, seen in **Figure 5**. The standard also gives tolerances for component placement, and it states that "all leading deckboards shall be within ±1/4 in (±6mm) of their respected specified location. Other wood components shall be within ±1/2 in (±13mm) of their specified location, except that bottom boards shall not extend into the stringer notch. Maximum placement deviation shall be limited to one third of the component in any pallet. All similar components shall be placed parallel unless otherwise specified."



Deckboards and Stringerboards
Thicknesses: ±1/16 in. (±1.6 mm) maximum deviation (including target deviation of 1/32 in. [±0.8 mm])
Width: +unlimited, -1/4 in. (-6 mm) maximum deviation
Length: +1/8 in. (+3 mm), -1/4 in. (-6 mm) maximum deviation

Stringers and Blocks
Width: ±1/16 in. (±1.6 mm) maximum deviation
Height: ±1/16 in. (±1.6 mm) maximum deviation
Length: +1/8 in. (+3 mm), -1/4 in. (-6 mm) maximum deviation

Figure 5. Pallet component acceptable manufacturing tolerances from the NWPCA Uniform Standard for Wooden Pallets (NWPCA, 2014)

Pallet manufacturing can be performed manually, with a single head machine, or with a double head machine. Pallets that are assembled manually are typically built by two workers, producing 60-75 pallets a day. By using automatic nail guns or stapling machines, both of which are operated by air pressure, manual production can increase to 200-250 pallets per day by two people while still allowing for easily customizable designs (Eichler, 1976).

Viking Engineering is a popular company for producing pallet automation machines and equipment. They have five variations of pallet assembly machines. Each of their machines has the capability of producing from 500 pallets to over 2000 pallets per worker per shift. Their machines can be run by 1-3 operators, depending on the specific type of machine, and they automatically assemble pallets to programmed specifications. Although these machines are automatic, they still need to be loaded with components, including nails, deckboards, stringers, stringerboards, and blocks, by the operators. Some machines require the operator to place each of the deckboards in place. Others only require a stack of deckboards to be fed into the machine, which then places them in their designated location and nails or staples them to the stringers, stringerboards or blocks.

Viking Engineering’s least automated machine is their Champion 304A Classic. It requires a single operator and can produce upwards of 500 pallets per shift using both new and reclaimed components up to 60” in length. With this machine, the stringers and bottom deck (pre-assembled) are automatically fed into place by the machine. Then a worker places the boards in their designated locations, and the machine automatically nails them to the stringers. Once the pallets are fully assembled, they’re pushed down a conveyor and stacked by the machine in a location for the forklift to come and transport the stack of pallets.

Viking’s most automated machine is the Turbo 606. This can produce over 2,000 pallets per shift with three operators. The operators feed the machine with the necessary components, such as nails and deckboards. The stringers move down the line, and the top deckboards get nailed on first. The machine then flips the deck and stringers over and nails the bottom deck to the rest of the pallet. At the end of this process, the pallet is moved down the conveyor and stacked in a location to later be transported by a forklift.

1.1.4 **Materials**

It is estimated that 95% of the pallets used in the United States are made of wood (White and Hamner, 2005), both hardwood and softwood. In 2016, an estimated total of 8.6 billion board feet of lumber was used to make pallets, of which 45% was hardwoods and 55% was softwoods (Gerber, 2018). Regardless of the species used, pallets are typically made from the lowest grade of lumber due to cost. Pallet components are often purchased through a third-party supplier by precut lengths, although some pallet manufacturers have their own lumber cutting equipment that they can use to cut cants and boards to the widths and lengths required (U.S.D.A. Forest Service, 1971). The moisture content of lumber can vary depending on the drying requirements specified. Lumber with moisture content that is closer to the moisture content of the air during use is more beneficial for pallet assembly because it is less likely to warp and split. Wood shrinks significantly in the tangential and radial directions, however does not significantly shrink in the longitudinal direction, which can lead to warping. This has an effect on pallet performance and pallet life expectancy. Lower moisture content can also help prevent decaying and molding in lumber, which extends the life expectancy of pallets. Decay resistance is also affected by the species used as well as the extractives in the lumber and amount of heartwood and sapwood (U.S.D.A. Forest Service, 1971). The species of wood used for pallets varies by region based on what is available in that region for manufacturers. The distribution of hardwoods compared to softwoods used by region was also found by Gerber (2018) and can be seen in **Figure 6**.

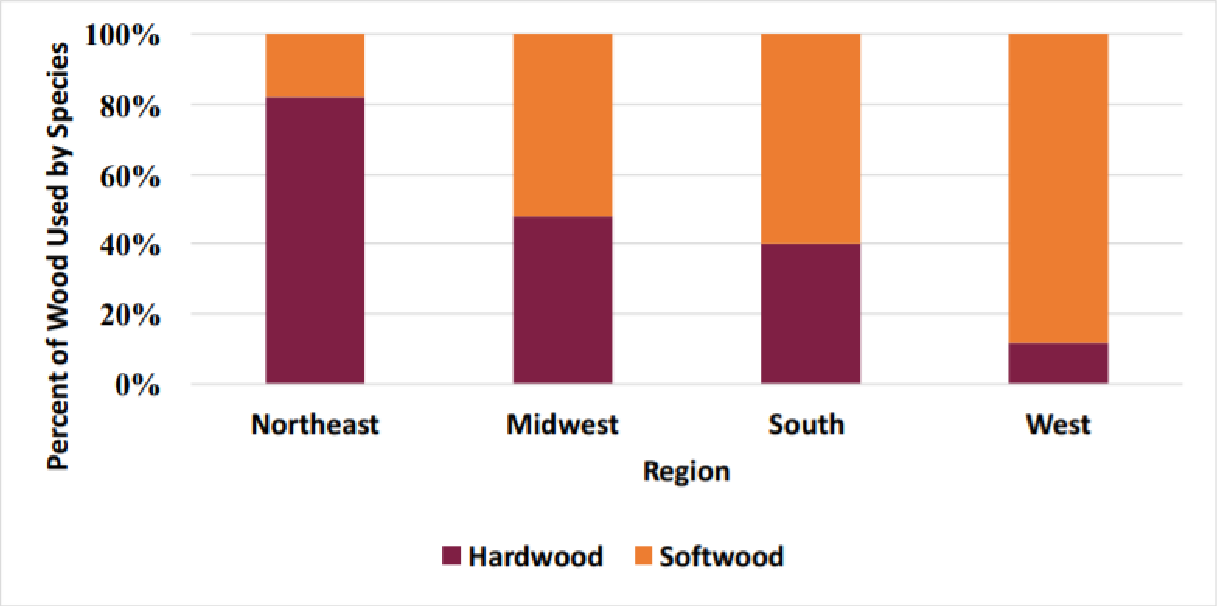
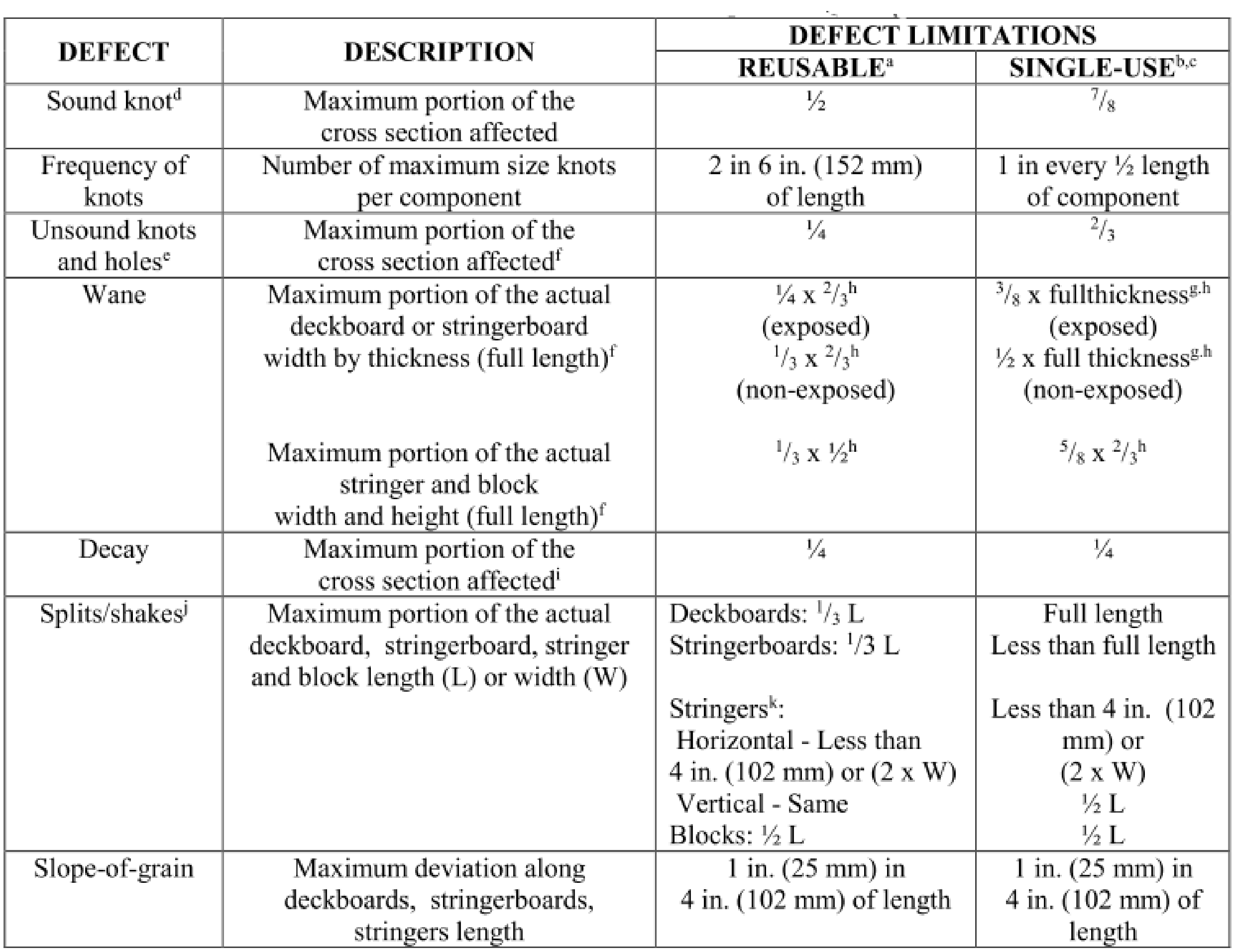


Figure 6. Regional distribution of wood used for pallet production by region (Gerber, 2018)

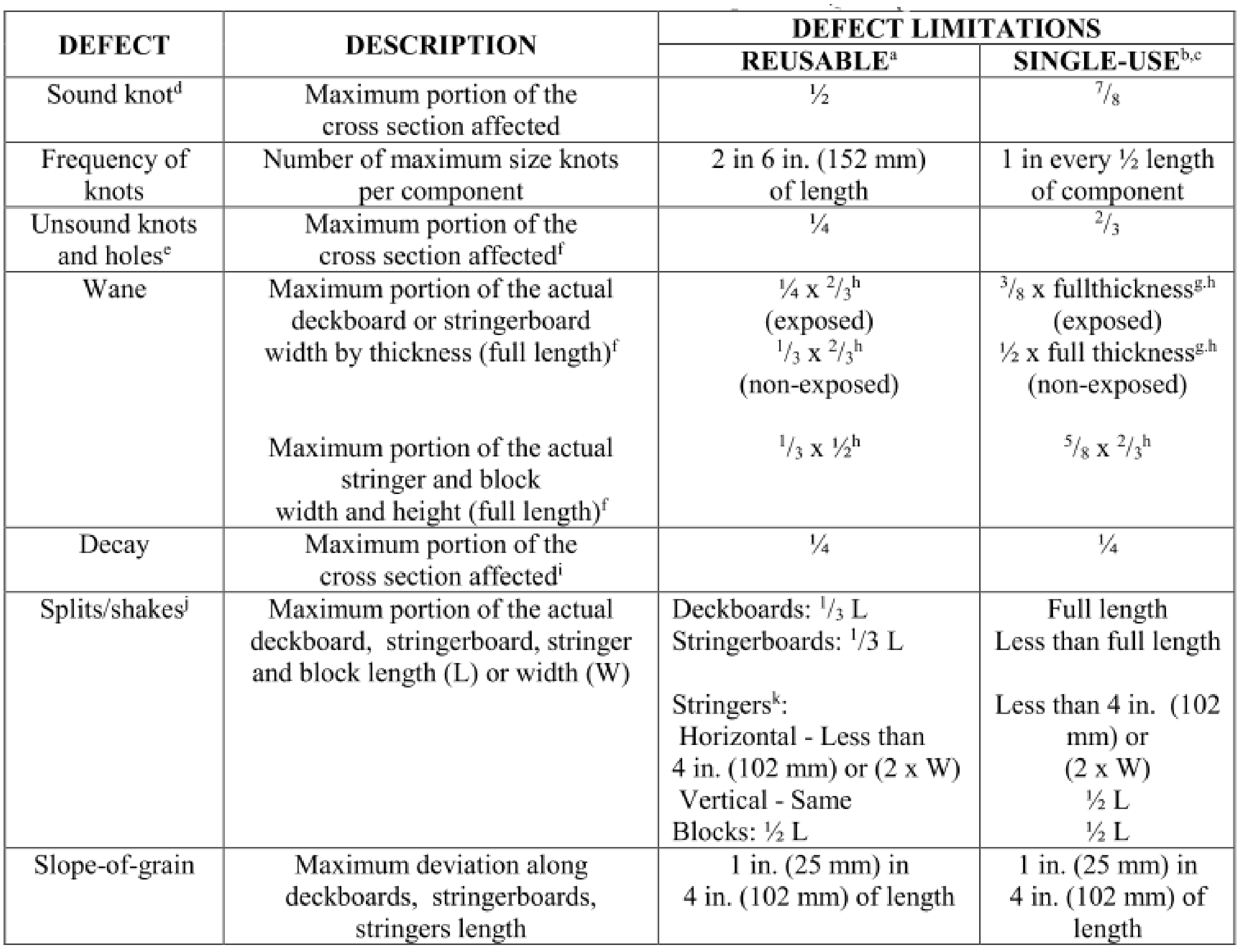
Hardwood use dominated the eastern region and softwood dominates the western US. Lumber can be specified as “green,” “shipping dry,” “air dried,” and “kiln dried.” Hardwoods are often bought by pallet manufacturers when it is green due to the lower cost and because it is easier to nail (U.S.D.A. Forest Service, 1971). Green lumber is lumber which has been freshly cut or sawn, and it has not had any drying treatment or conditioning. Its moisture content is above the fiber saturation point of the wood. Above the fiber saturation point there is no change in dimension based on change in moisture content. Lumber is also often bought "shipping dry," meaning that it has been partially dried, either by air or kiln, to lower the shipping costs by reducing the lumber's weight as well as lowering the likelihood of mold forming in transit. Shipping dry lumber can still be above the fiber saturation point, but it still has a lower moisture content than green lumber. Air dried lumber has been left to condition for a period of time to allow for the moisture content to become closer to the expected ambient conditions. In the United States, air dried lumber can have a moisture content as low as 12-15%, but it is typically higher (U.S.D.A. Forest Service, 1971). Kiln dried lumber has been dried in a kiln for a period of time to meet a specified average moisture content. Since the moisture content of wood after kiln-drying is an average value, the moisture content of the individual components could be slightly above or below the average. Wood moisture content can be determined either by the oven dried method, or with electronic moisture meters (U.S.D.A. Forest Service, 1971).



DEFECT	DESCRIPTION	DEFECT LIMITATIONS	
		REUSABLE[a]	SINGLE-USE[b,c]
Sound knot[d]	Maximum portion of the cross section affected	½	7/8
Frequency of knots	Number of maximum size knots per component	2 in 6 in. (152 mm) of length	1 in every ½ length of component
Unsound knots and holes[e]	Maximum portion of the cross section affected[f]	¼	2/3
Wane	Maximum portion of the actual deckboard or stringerboard width by thickness (full length)[f]	¼ x 2/3[h] (exposed) 1/3 x 2/3[h] (non-exposed)	3/8 x fullthickness[g,h] (exposed) ½ x full thickness[g,h] (non-exposed)
	Maximum portion of the actual stringer and block width and height (full length)[f]	1/3 x ½[h]	5/8 x 2/3[h]
Decay	Maximum portion of the cross section affected[i]	¼	¼
Splits/shakes[j]	Maximum portion of the actual deckboard, stringerboard, stringer and block length (L) or width (W)	Deckboards: 1/3 L Stringerboards: 1/3 L Stringers[k]: Horizontal - Less than 4 in. (102 mm) or (2 x W) Vertical - Same Blocks: ½ L	Full length Less than full length Less than 4 in. (102 mm) or (2 x W) ½ L ½ L
Slope-of-grain	Maximum deviation along deckboards, stringerboards, stringers length	1 in. (25 mm) in 4 in. (102 mm) of length	1 in. (25 mm) in 4 in. (102 mm) of length

Figure 7. Minimum Lumber Component Quality from the Uniform Standard for Wooden Pallets (NWPCA, 2014)

Wood is an extremely variable material and because it is so variable, it can have many defects, which can make it disadvantageous to use. Standards such as the National Wooden Pallet and Container Association's Uniform Standard for Wooden Pallets give the limitations for what defects levels are acceptable and which are not acceptable.



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	Maximum portion of the actual stringer and block width and height (full length)[f]	1/3 x ½[h]	5/8 x 2/3[h]
Decay	Maximum portion of the cross section affected[i]	¼	¼
Splits/shakes[j]	Maximum portion of the actual deckboard, stringerboard, stringer and block length (L) or width (W)	Deckboards: 1/3 L Stringerboards: 1/3 L Stringers[k]: Horizontal - Less than 4 in. (102 mm) or (2 x W) Vertical - Same Blocks: ½ L	Full length Less than full length Less than 4 in. (102 mm) or (2 x W) ½ L ½ L
Slope-of-grain	Maximum deviation along deckboards, stringerboards, stringers length	1 in. (25 mm) in 4 in. (102 mm) of length	1 in. (25 mm) in 4 in. (102 mm) of length

Figure 7 shows the defect limitations for lumber used in pallet construction. Pallets are assembled using the lowest quality material available since appearance is not an issue and raw material cost has a large influence. Hardwood lumber grades typically purchased by pallet manufacturers are typically NHLA grades, 2C, 3A, and 3B common. However, pallet part quality is further limited by the pallet standards.

1.1.5 **Testing**

The load capacity of the pallet is dependent on the type of load carried by the pallet and the type of condition used to support the pallet. These support conditions include floor support, fork time support, rack support, sling support, and conveyor support. There are two main testing standards that provide guidelines for pallet testing; ASTM D1185 (ASTM, 2009) by the American Society for Testing and Material, and the International Organization for Standardization (ISO). ASTM D1185 (ASTM, 2009) is commonly used for domestic pallets which are those that stay in the United States while ISO 8611 (ISO, 2011) is used for pallets that will end up outside of the United States or are expected to be shipped internationally.

Both standards are used to evaluate pallet strength under static and dynamic loads. The nominal load capacity of a pallet is the lowest load the pallet can support safely in a specified condition, regardless of the type of load on the pallet. The maximum working load is for a specified load on the pallet ASTM D1185 (ASTM, 2009) references an airbag applied directly onto the pallet to simulate a flexible load. ISO 8611 (ISO, 2011) references load beams on concentrated areas based on the support condition being tested. Both test methods refer to various impact tests to determine durability.

1.1.6 Load Capacity

Determining a pallet's load capacity is important in making sure that it is being used in the proper manner, allowing for a safe environment and preventing product loss. The load capacity is dependent on the support conditions, which are determined by the handling and storage conditions in the distribution environment. Main support conditions include forklift support, conveyor support, single and multiple stacked floor storage, and warehouse rack storage.

During a forklift support, the top deck of the pallet is supported using two 4 in. wide supports simulating the two forklift or pallet jack tines. The span between the supports is dependent on the testing standard. This support condition puts a lot of bending stress on the top deckboards and shear stress on connection between the pallet components. In a conveyor support condition, the load is applied on the bottom deck. During testing the pallet is turned upside down and when following ASTM D1185 (ASTM, 2009) or ISO 8611 (ISO, 2011) two parallel load beams, whose distance are determined based on the pallet dimension, are used to apply a concentrated load simulating twin track conveyors or narrow rack supports. In a single stacked support condition, the bottom deck of the pallet is fully supported while load is applied to the top deck. A single stacked support condition reflects a pallet being stored on the ground with only the weight of the unit on the pallet. During a multiple stacked support condition, the bottom support would be the same, but pallet would be supporting the weight of more than one unit. In a warehouse rack support condition, the pallet is supported by two 2 in. beams close to the end or side of the pallet. The span between the supports is dependent on the used testing standard. This support condition is often the one that limits the functionality of the pallet as the whole pallet is stressed in bending (ASTM, 2009) causing shear and tension stresses.

During the testing, the pallet is commonly loaded until failure to determine its strength. Failure is reached when a pallet component breaks or if the pallet deflects past an allowable limit. The resulting pallet strength is then adjusted to determine a load for a creep test. A creep test is conducted using the predetermined load to verify what load level can be safely supported by the pallet. The creep duration and the appropriate deflection limits are defined by the applicable ASTM or ISO standard.

1.1.7 Durability

Pallet durability is based on a pallet's resistance to damage. Damage commonly occurs during material handling when the stringers or blocks of the pallet is impacted by the tip of the fork tines or when the edge of the top end deckboards are impacted by the heel of the fork tines (Eichler, 1976). Since this damage is common, ISO 8611 (ISO, 2011) and ASTM D1185 (ASTM, 2009) testing standards provide standardized testing to stimulate this effect. The tests are comparative, and they mainly measure how many impacts a block or a top leading edge deckboard can withstand. **Figure 8** shows the setup for a top leading edge deckboard test, and **Figure 9** shows the setup for a block impact test. Both tests are conducted similarly, where the pallet is lifted on a dolly to a specified height and dropped to impact the fork tines repeatedly until failure. In these tests, failure is defined when a pallet component breaks or when a pallet joint connection fails (ISO 8611, 2011).

Pallet rigidity can also be tested using free-fall drop tests. These tests measure the resistance to impact and the rigidity of the pallet. The pallet is suspended in the air diagonally and dropped on its corner, as seen in **Figure 10** (ISO 8611, 2011). Stern et al (Stern, Wallin, & Whitenack, 1985) found a statistically significant correlation between the rigidity of a pallet, tested using a free-fall corner drop test, and the expected durability of the pallet. They stated that the rigidity can serve as an indicator of a pallet's susceptibility to damage, and therefore durability and expected life.

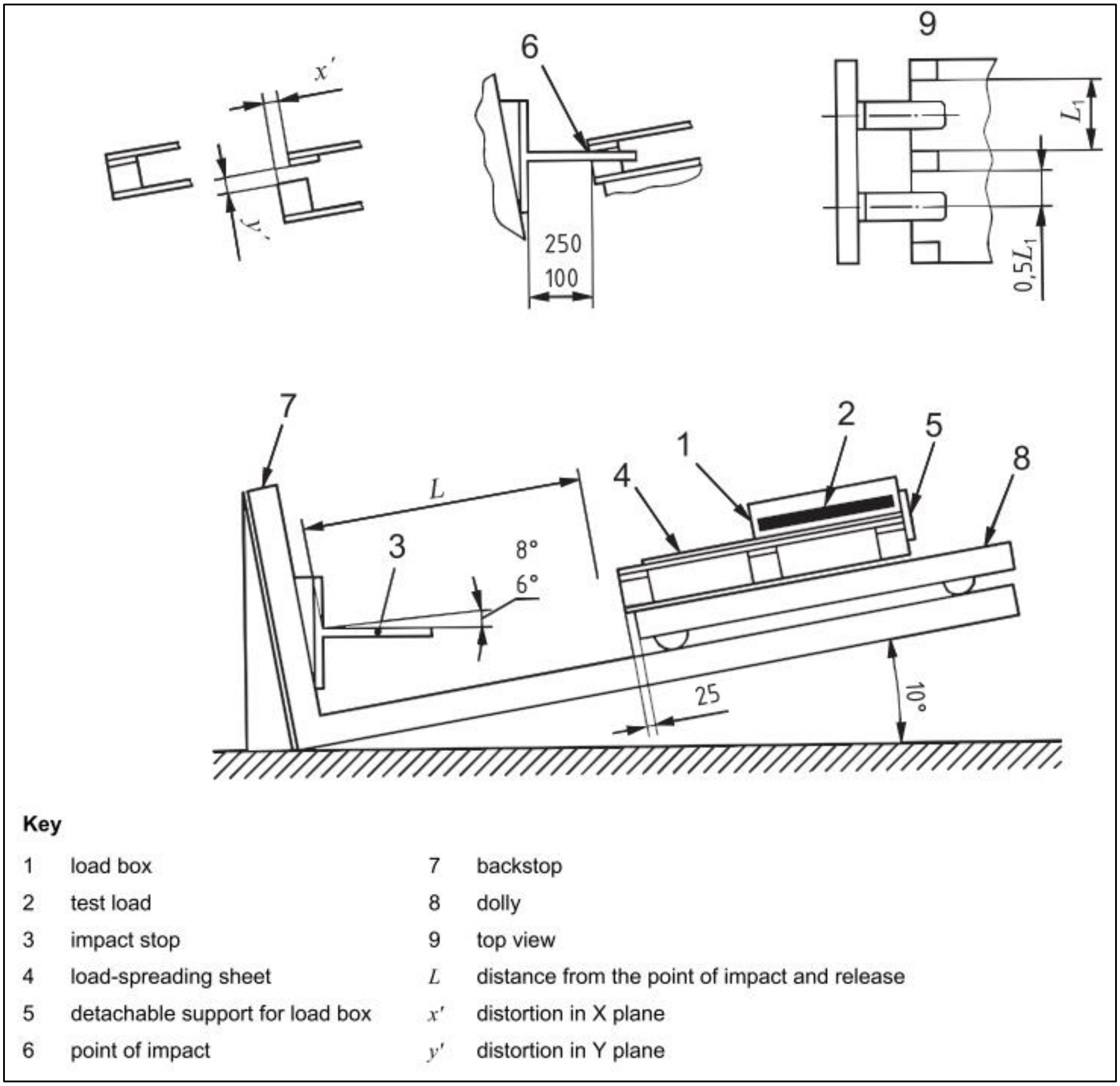
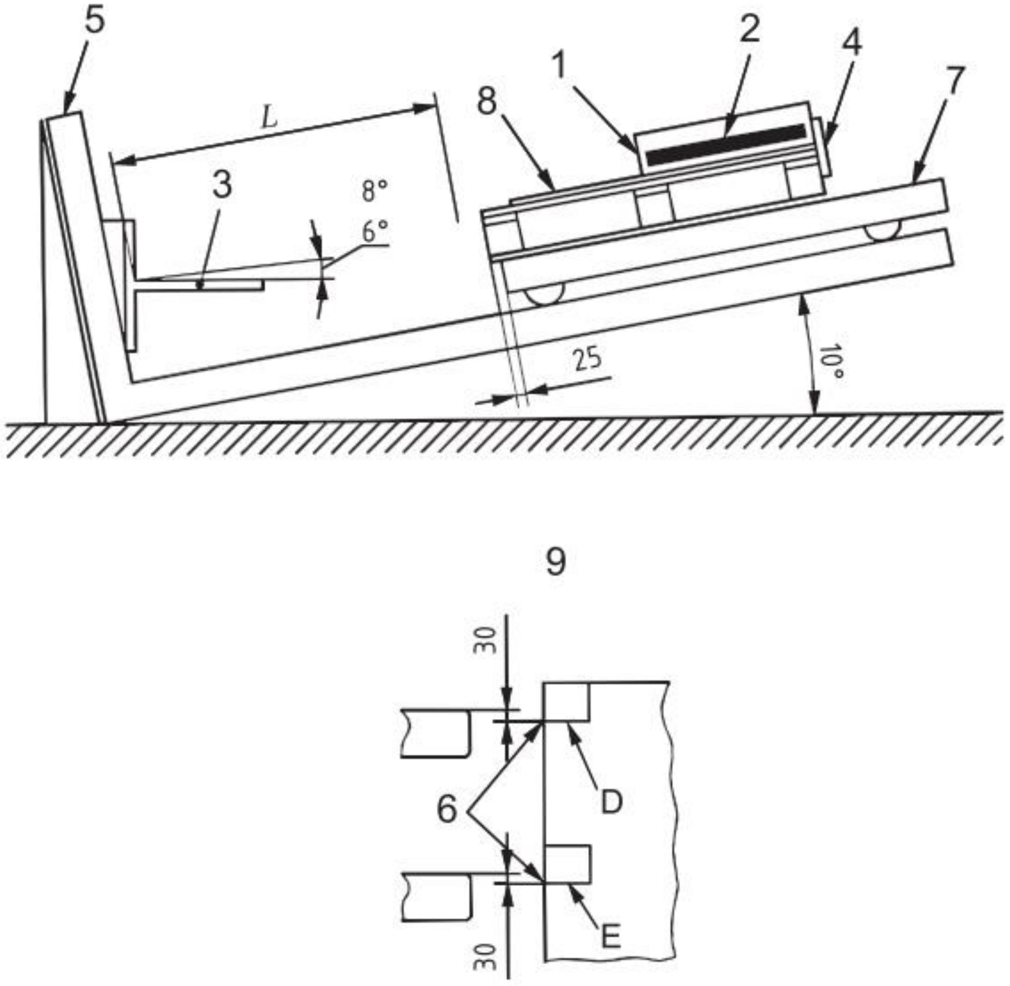


Figure 8. Schematic of how to conduct a top leading edge deckboard impact test from ISO 8611 published in 2011 (ISO, 2011)



Key

1	load box	6	points of impact
2	test load	7	dolly
3	impact stop	8	load-spreading sheet
4	detachable support for load box	9	top view
5	backstop	*L*	distance from the point of impact and release

Figure 9. Schematic of how to conduct a block impact test from ISO 8611 published in 2011 (ISO, 2011).

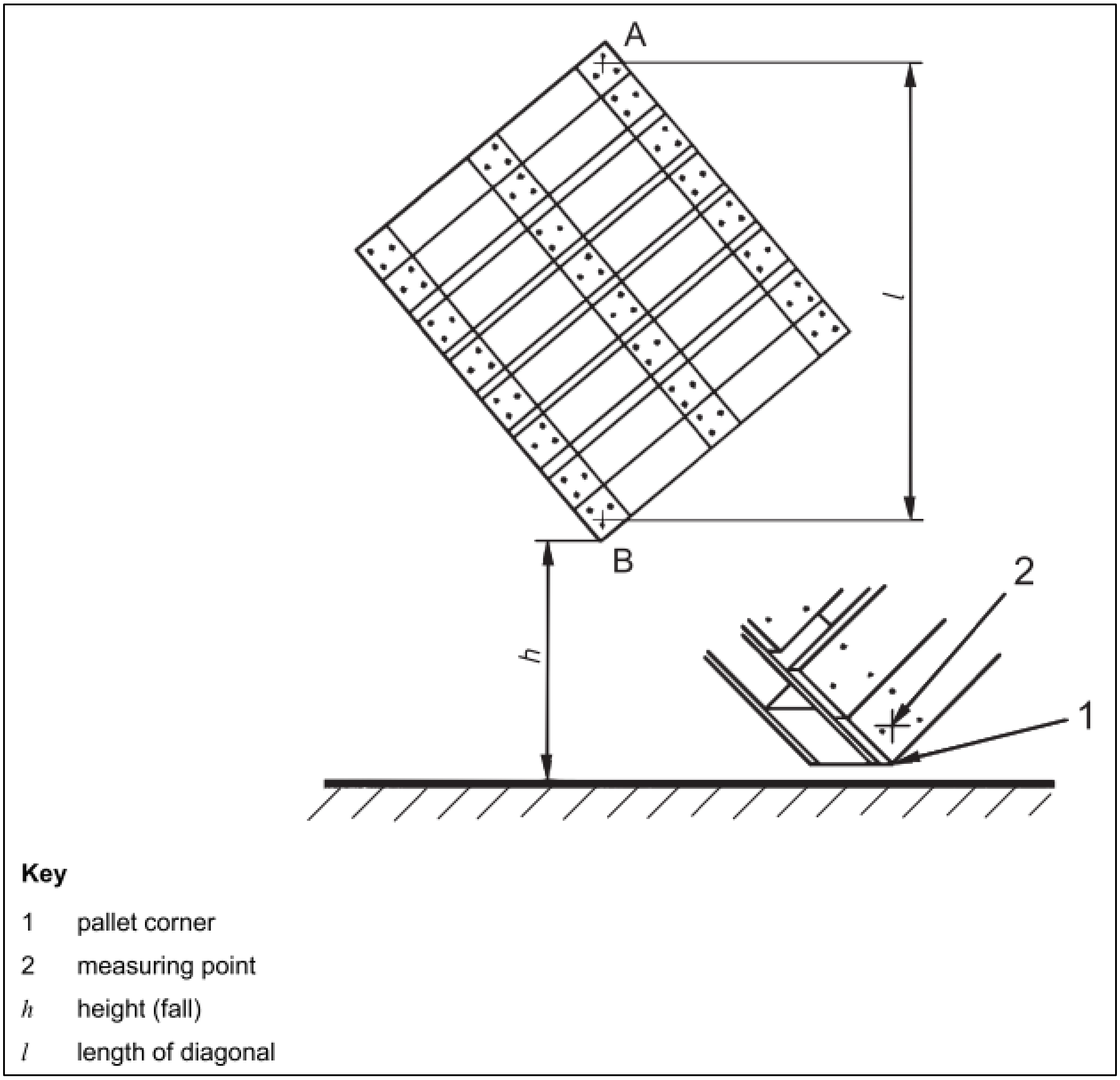


Figure 10. Schematic of how to conduct a corner drop test from ISO 8611 published in 2011 (ISO, 2011).

1.1.8 Repair

Wooden pallets have limited use expectancy since they constantly get damaged during user mishandling with forklifts and pallet jacks (Eichler, 1976). ISO 18613 (ISO, 2003) and the NWPCA Uniform Standard for Wood Pallets (NWPCA, 2014) provide limits. The components which receive the most damage in wooden pallets are the top leading edge deckboards, and the bottom deckboards. Leading edge deckboards are most commonly damaged by impacts of forklifts. Bottom deckboards are often pried off when pallet jack wheels are placed on them and the unit load is lifted (Eichler, 1976). When these pallets are damaged and deemed unusable or have fulfilled their purpose and cannot be used anymore, they need to be disposed of by the user, repaired by the manufacturer, or recycled by a third party.

Pallet disposal is often an extra unwanted handling issue for users, so companies go through third party management companies. Some third-party management companies include pallet pooling companies, where pallets are rented or leased and are shared by many users. These pallets are picked up and repaired by the pooling company between uses.

Other third-party management companies include pallet recyclers who pick up used pallets, so they can dismantle, repair, and remanufacture pallets (Bejune, Bush, Araman, Hansen, & Cumbo, 2002). Once used pallets reach the pallet recycler's facility, they are separated based on how many components are broken. Pallets that have no broken or damaged components are sold as is. If only a few components are broken, then the pallet will usually be repaired for resale. Pallets are repaired with either new components or with used components from dismantled pallets. Pallet repair is often performed manually, using a repair table, crowbars, and sledge hammers by one or two people. Components are to be replaced with the same dimensions and quality of the original or to a specified dimension and quality, based on the specifications of the new pallet, using either new or salvaged components (ISO, 2003). Dismantling machines which remove and separate components from a pallet, produce a higher percentage of salvage. Salvaged components can be used to repair pallets with few repairs needed (Eichler, 1976). Unusable components or unrepairable pallets are ground up to later be sold as fuel, animal bedding, or landscape mulch. Less than 1% of recovered pallets end up in landfills (Bejune et al., 2002).

Pallets which are completely reassembled using some or all salvaged components are called remanufactured pallets, while pallets which have components replaced are called repaired pallets. Repaired pallets are classified based on how many of its stringers have repairs. If a pallet has no companion components, however it may have a metal plate, it is a class 1 or grade A pallet. Class 2 or grade B pallets have one or two stringers that have been repaired either with a companion component, such as a plug, notched block, or companion stringer. Any pallet that does not meet the qualifications for a class 1 or class 2 pallet is classified as a class 3 or grade C pallet (NWPCA, 2014).

1.2 Fasteners

Pallet joints are connected using various methods depending on the pallet and the material. These include metal fasteners, adhesives, welds, interlocks, or a combination. For wooden pallets connections are mostly done using metal fasteners. Nails, staples, bolts, wood screws, and lag screws are all classified as fasteners in pallets. Driven fasteners include nails and staples. There are five classifications of nails which are plain shank, helically threaded, annularly threaded, fluted, and twisted square wire. A diagram of various driven fasteners from ANSI MH1 (MH1 Committee, 2005) can be seen in **Figure 11**. Staples are classified based on the cross-sectional shape of the wire, which are either rounded or square (NWPCA, 2014).

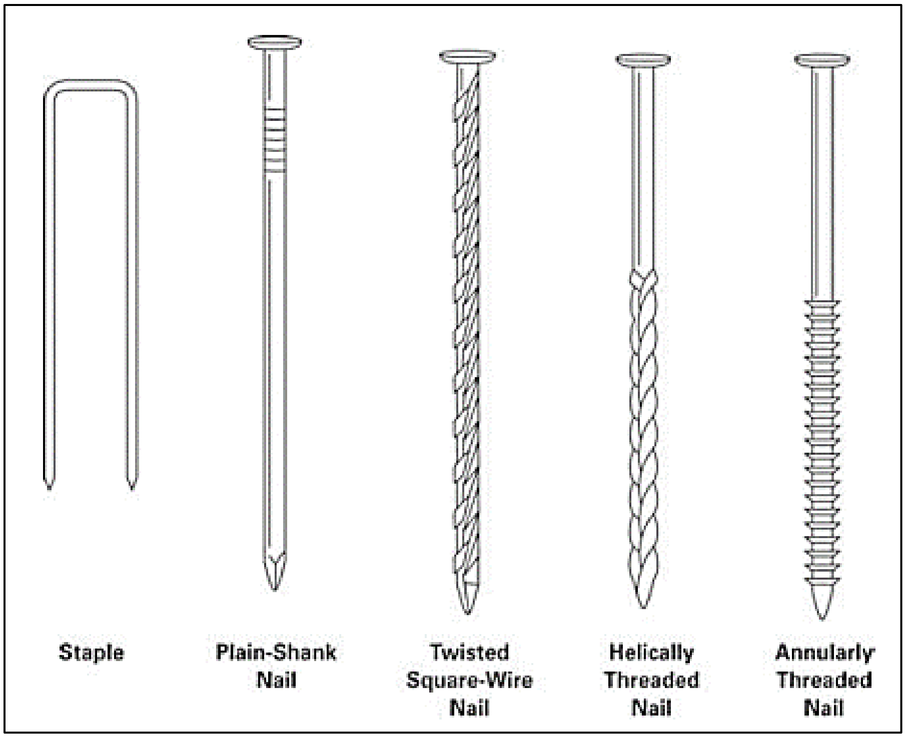


Figure 11. Examples of driven fasteners for pallets from ANSI MH1 (MH1 Committee, 2005)

Fasteners quality is based off different specifications of the fastener including tread angle, thread crest diameter, head diameter, fastener length, thread length, and MIBANT angle. **Figure 12** from the Uniform Standard for Wooden Pallets (NWPCA, 2014) shows how characteristics of a nail are measured. The material from which fasteners are made of is regular-stock steel, stiff-stock steel, or hardened steel. Regular-stock steel has “no special mechanical properties,” stiff-stock steel is stiffer and has more resistance to bending than regular-stock steel, and hardened steel has been heat-treated and tempered so that the fastener can have even more resistance to bending. Hardened-steel can be a dangerous material to use, because if the fastener breaks, particles of it can fly out and become hazardous to workers, particularly during assembly (NWPCA, 2014).

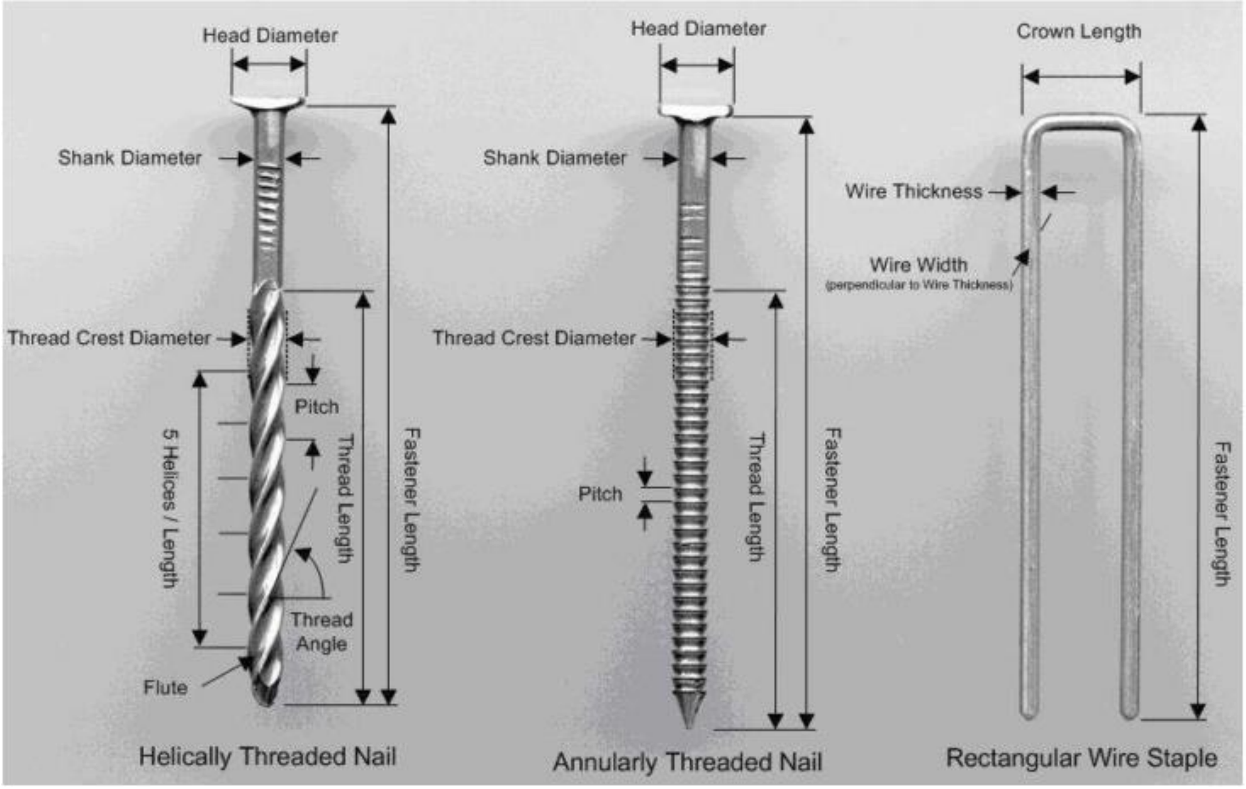


Figure 12. Measurements of pallet fastener characteristics from the Uniform Standard for Wood Pallets (NWPCA, 2014)

1.2.1 **Testing**

Pallet performance is greatly influenced by fastener quality, quantity, location, and type used. ANSI MH1 provides information on how to determine expected fastener performance, by using the fastener withdrawal index (FWI), the fastener shear index (FSI), head pull through (HPT) resistance to measure performance. During pallet usage failure most commonly occurs at the joints (White & Wallin, 1988) during which the fastener is withdrawn from a stringer or block, or when a deckboard pulls through the head of the fastener. Head pull through is generally associated with the bending of the nail and the resulting splitting of the deckboard.

Fastener withdrawal index (FWI) is an estimated value for resistance of a nail or staple to be withdrawn. It is calculated based on the wire diameter, thread crest diameter, thread length, and the number of helixes along the thread length. ANSI MH1 (MH1 Committee, 2005) recommends that the calculation not be applied for fasteners with a discontinuous thread, but it can be performed for staples and annularly threaded nails with some extra calculations. Fastener shear index (FSI) is a value that represents a fastener’s resistance to lateral deformation which can occur during withdrawal or head pull through. It is dependent on the wire diameter and its resistance to impact bending, which can be determined using a MIBANT test. For nails, FSI is calculated using the wire diameter and MIBANT angle, and for staples it is calculated using the width and thickness of the flattened-wire staple. The MIBANT angle is derived from a test that measures a fastener’s resistance to bending during impact. The test requires a specific piece of equipment used where a specific weight from a specific height is dropped onto the fastener being tested, which causes the bending of the fastener. The angle change of the fastener after impact is determined and that is the MIBANT angle.

Performance is primarily estimated using the fastener withdrawal index and the fastener shear index, however if a fastener's head pull-through resistance is lower than its fastener withdrawal index or fastener shear index then performance is estimated using the head pull-through resistance. Head pull-through resistance in both nails and staples is based on the oven-dry, specific gravity and the moisture content of the component being fastened. In nails, it is also a function of the wire diameter of the fastener. In staples, it is also determined by the "flattened staple-wire width, measured perpendicular to crown axis" (MH1 Committee, 2005).

1.2.2 Pallet Performance

Durability and performance of a pallet are directly related to fastener quality. Stapled pallets have an average of 64% shorter life expectancy than nailed pallets, and they require 2–2.5 times as many staples as nails to be equivalent in life expectancy and cost per use. Nails also provide significantly higher rigidity to the pallet than staples, which helps improve pallet life expectancy and lowers cost per use (Stern, 1980). Factors that affect pallet durability are the design and construction of the pallet, the handling conditions, the wood species, the moisture content of the components, the design of fasteners used, and the number of fasteners used. When the number of the fasteners in the pallet is increased by just 5-6%, the durability of the pallet increases by 56% (White & Wallin, 1988).

Approximately 77% of pallet damage occurs at the joints, primarily as the fasteners withdraw from the stringer or stringerboard or as the nail head pulls through the deckboard. Fastener withdrawal is dependent on the characteristics of the nail or staple, and it is more likely to happen than the nail head pulling through the deckboard. Head pull-through primarily occurs due to weak components, since most nails are overdesigned to resist it (White & Wallin, 1988). Nails popping up is also an issue that occurs when fasteners are loosened during transportation, due to the vibrations that the pallet experiences (Caldicott, 1991) or due to the lumber shrinking and swelling due to changes in moisture content during transportation. The likelihood of nail pop-ups can be decreased by using dried lumber and maintaining a stable moisture content throughout the usage of the pallet (Stern, 1956). Nail popping in pallets leads to the pallet either needing repairs or needing to be disposed of (ISO, 2003).

1.3 Wooden Pallets and Adhesives

The quality of a pallet is greatly affected by the quality of the joints since the majority of failures occur at the joints. By improving the quality of the fasteners, pallet life can be significantly increased with minimal cost increase (White, 1990). Nails are low cost fasteners that can provide good performance and allow fast production speeds. Although nails have multiple benefits, they can cause issues in wooden pallets such as wood splitting, nail head pop up, and product damage. Various studies have been conducted to compare the performance of wooden pallets assembled with nails to pallets assembled with adhesives. An ideal adhesive would have good gap-filling characteristics, be weather and moisture resistant, have low emission of volatile organic compounds (VOCs), be easy to apply, clean, and be disposed of, have a short assembly time, a long pot-life, a low cure temperature, be resilient to creep, relaxation, and impact loading, and be affordable (Mitchell, 1997).

(Robert, Wis, Service, & Service, 1973) compared the performance of pallets using different assembly methods, including nails, staples, and four different elastomeric adhesives. Various species of wood were used, both green (more than 30% moisture) and dry (12% or less) with 1/32" and 1/16" bondlines. The American Plywood Association (American Plywood Association, n.d.) recommends in a technical note that elastomeric adhesives be used in plywood pallet assembly with an ideal bondline thickness of 1/32 in. to 1/16 in., which can be achieved using shims. However, Kurtenacker (Kurtenacker, 1973) found no significant differences based on the thickness of the bondline in wood pallets. He also found that the amount of wood failure was dependent on the density of the wood, with low-density wood having higher amounts of wood failure and high-density wood having lower amounts of wood failure. Various impact and static compression tests were conducted on corner connections and whole pallets; however, not all combinations of each variable were tested, and limited repetitions were conducted. The results showed some promise for two of the adhesives tested with limitations. But, it was concluded that the other two adhesives were not suitable for pallet applications.

(Frackiewicz, 1983) also compared pallets assembled using adhesives to those assembled with nails, as well as a combination of both. Various adhesives were tested on a smaller scale before deciding to test an epoxy resin on a larger scale due to it having greater strength than the other adhesives tested. Stringer pallets made of green oak were tested in compression for strength and with drop tests for impact resistance. The pallets assembled with the epoxy resin presented higher stiffness and higher strength than those assembled with nails and their joints were very resistant to rotation and deflection due to the high stiffness. On average, the joints with epoxy could carry 1.68 times the initial load than the nailed joints, and the joint assembled with both nails and adhesives could carry 2.45 times the load. Joints assembled with both methods had initial failure in the glue bondlines with the nails still having resistance until a later failure due to the nails. Connections that had failure in the glue bonds exhibited sudden failure which in use could potentially be hazardous. Frackiewicz mentions that there could be issues with epoxy being used in pallets, such as cost and cure time since epoxy resin is costly compared to nails and has a relatively long cure time. He also points out that there were issues in bonding due to the high moisture content of the wood.

(Mitchell & White, 1998) looked at the performance of green and air-dried GMA stringer pallet connections assembled with various adhesives. Adhesives tested include polyvinyl acetates (PVA), elastomers, reactive hot melts, urethanes, epoxies, soy hydrolysate-phenol/resorcinol formaldehyde (soy-PRF), and urethane-isocyanate. Similarly to Frackiewicz (Frackiewicz, 1983), Mitchell found that epoxies were not suited for pallet manufacturing due to long curing time, high cost, and difficult application. Hot melts and Titebond elastomers were determined to be candidates for future testing due to ease of handling and relatively short assembly time. Of all adhesives tested, the one with the best performance was a cross-linking PVA. Mitchell (Mitchell, 1997) also looked at the effect of surface smoothness of pallet components on the strength of joints made with a polyvinyl acetate (PVA) glue. It was found that joints assembled with planed lumber had a higher maximum load carrying capacity, as well as a higher stiffness. The average maximum load for rough sawn joints was 975lbs., while in planed joints it was 1402lbs. The stiffnesses were 2338lbs./in and 3541 lbs./in respectively. Mitchell points out that PVA is not often looked at for pallet application due to limitations such as long cure time, limited outside application, and potential deformation under constant load. While planed joints had better performance, it may not be beneficial in manufacturing due to a greater production cost.

1.4 Adhesives

Adhesives are substances that attach the surfaces of two materials, adherends, together through interfacing forces, interlocking forces, or a combination. Interfacing forces include van der Waals, dipole-dipole, dipole-induced dipole, and dispersion forces. Interlocking forces, also known as mechanical interlocking or bonding, is when the surfaces of both adherends are penetrated while the adhesive is liquid, ideally multiple cells deep, and creates an interlocking effect between the materials (Frihart & Hunt, 2010).The surface of a substrate attributes largely to the quality of the bond that can be produced. A clean surface and smooth, free of debris or surface irregularities, is needed to provide proper wettability of the surface. Wood extractives also have an effect on the surface quality and can lower the wettability from the adhesive; e.g. species such as southern pine or Douglas-fir which are highly resinous lower the ability for the adhesive to properly wet the surface. Ideally the surfaces should be planed parallel to each other to improve mechanical interlocking and achieve a better bond.

The density of the wood influences the strength of the bond. As the density of the wood increases, up to 0.7-0.8 g/cm^3, the strength of the joint and the amount of wood failure increase. Above this density both decrease because in denser woods the cells are closer, there is less porosity, and don’t allow adhesive penetration. High wood failure is preferable because the strength of the connection can be based on the known strength of the wood rather than of the bondline of which the strength can be reduced if it is of poor quality. The moisture content of the wood and any changes in the wood and in the relative humidity of the surrounding environment also have a large influence on the strength of the connection. As these changes occur they cause dimensional changes in the wood. Shrinking and swelling causes stresses in the adhesive bond which could weaken or even break the connection. Stresses in the wood can be reduced by bonding the adherends in the same grain direction since they would have more similar shrinkage and swelling properties. More elastic adhesives, such as structural adhesives, can transfer stresses between adherends more effectively without causing damage (Vick, 1999).

The stiffness and the thickness of the adhesive have a significant effect on how the stresses between the adherends are distributed. If the stiffness of the adhesive is similar to the adherends then the stresses are more evenly distributed. A stiffer adhesive decreases the shear stress in both the adhesive layer and in the adherends. Thinner bondlines also help decrease the shear stresses in the connection, but the effect of bondline thickness is less significant than the stiffness of the adhesive. Increased adhesive stiffness increases the stresses in the adhesive and distributes them over a large area, whereas a more flexible adhesive allows for lower stress levels (Groom & Leichti, 1994). In pallet use elastomers are recommended due to their properties (American Plywood Association, n.d.). Elastomers are cross-linking polymers with high molecular weights that are viscoelastic, having properties of both solid and liquid states. They are flexible and resilient to elongation due to a high modulus of elasticity and have good resistance to heat, cold, and moisture. They are versatile, allow quick assembly, are economical to use, and can be altered to meet the users’ needs (Pizzi & Mittal, 2003).

Adhesives can be categorized by their performance and resistance to environmental exposure and moisture. Adhesives that can withstand repeated soaking at drying over a long period of time while maintaining their strength and rigidity are fully exterior structural adhesives. Structural adhesives can be stronger and stiffer than the wood it is bonding and allow for higher performance in a connection. While they are strong and highly resistant to deterioration in service they require better surface, assembly, and curing conditions to bond properly. Limited exterior adhesives, or semi structural, cannot withstand long term exposure to water and heat while maintaining performance, but they are able to withstand short term exposure. They also cannot support loads for long periods of time. Nonstructural, or interior, adhesives can equal the strength and rigidity of bonded wood in dry conditions. They do not maintain their performance when exposed to high amounts of moisture but are more resistant to inconsistencies in surface, assembly, and curing (Frihart & Hunt, 2010).

Adhesives can set, cure, or harden in three ways: loss of solvent, cooling, or chemical polymerization. Solvents are lost through evaporation or through diffusion in the wood. Cooling occurs in thermoplastic adhesives which are liquid in high temperatures but solidify once their temperature decreases, such as polyvinyl acetate and hot melts. Their solidification is not permanent and if they are reheated they can soften. They typically have lower resistance to moisture and heat, and do not support high loads for long periods of time. Chemical polymerization occurs in thermosetting adhesives through a chemical reaction as a single or multiple part system. A catalyst can be added to accelerate the reaction and decrease the curing time. Thermosetting polymers do not soften when reheated due to permanent chemical changes that occur during curing. They have high resistance to moisture and can support high loads for long periods of time without deforming. Some examples are epoxies, melamine-formaldehyde, urea-formaldehyde, and isocyanate adhesives (Frihart & Hunt, 2010)

2 Manuscript

2.1 Introduction

The most commonly used pallets are ones made of wood and put together with nails or staples. These are assembled quickly for a relatively low cost, and once assembled, they are immediately ready for use. Wooden pallets are strong and durable, and nails provide more strength and durability at a low cost. The processes for manufacturing, repair, and disposal of wooden pallets are already in place, and they are efficient and sustainable. However, while they are commonly used and have a lot of benefits, using wood pallets can result in problems. Most of the failures in wooden pallets comes from the connections, and nailed connections most often fail by the nail head pulling through a deckboard, the nail withdrawing from the stringer or stringerboard or block or a combination of the two. Nails can also cause splitting in wood, which can lead to the need for repairs, and if they're exposed, nails can be dangerous to personnel during the handling process, and they can cause damage to products. Adhesives could be a potential solution to these problems because having only adhesive connections on the pallet would take away the possibility of metal being exposed to cause dangers and damage. Also, adhesives would not create concentrated high stress points along the wood of the pallet like nails do. While previous studies have focused on the performance of adhesives in single use stringer pallets, primarily made of oak, this study looks at reusable pool block pallets made of southern yellow pine (*Pinus echinata*).

In a pallet, there are two directions in which the wood aligns: parallel to the grain and perpendicular to the grain. There are also two types of forces experienced by a pallet connection: shear and tension. The front connection of a block pallet connects the deckboard to the stringerboard. This block contains both types of wood alignments and experiences both types of forces. It is also the connection that experiences the most damage due to handling. An adhesive would have to be able to bond with the wood in both directions while being able to withstand similar or higher loads when in use. To help improve the bond, a cold press could be used to apply pressure. The connection needs to be allowed enough curing time to develop strength for good performance. The amount of curing time and the amount of pressure applied can be adjusted, and these changes could affect the strength of the connection. Using the ISO 12777-3 (ISO, 2002) protocol this study is an evaluation of the effect of these changes and ascertains how a pallet connection made only with adhesives compares to a connection made with nails.

2.2 Objectives

The main objective of this project was to compare the performance of pallets with connections glued together using commercially available adhesives to pallets with connections secured by nails commonly used on block class wooden pool pallets.

Specific objectives of the study are:

- To investigate the effect of pre-compression pressure applied during the application of an adhesive on the strength of the pallet connection.
- To investigate the effect of curing times on the strength of the connection
- To compare the strength of pallet connections constructed using commercially available adhesives to connections made with common pallet nails.

2.3 Materials

2.3.1 **Wood**

All of the lumber in the pallets used for this research project was southern yellow pine (*Pinus echinata*) that had been kiln dried to 19% moisture content. The samples were prepared using only lumber that was as close to straight grain as possible to avoid any visible wood defects such as knots. Samples were planed to a thickness of 0.6in. Moisture content in the samples was not controlled during the experiment. However, the average moisture content of the selected samples was measured at around 6-7%. Samples were cut to the dimensions listed in **Table 2**.

Table 2. Summary table of the dimensions of the pallet components that were used for the experiment.

Connection Type	Test Type	Component Dimensions (in.)		
		Deckboard	**Stringerboard**	**Block**
Nail	Shear	10 x 5.4 x 0.6	5.5 x 4.9 x 0.6	7.5 x 7.5 x 3.5
	Tension	10 x 5.4 x 0.6	5.5 x 4.9 x 0.6	7.5 x 7.5 x 3.5
Adhesive	Tensions Perpendicular	7 x 5.4 x 0.6	7.5 x 4.9 x 0.6	N/A
	Tension Parallel	N/A	10 x 4.9 x 0.6	7.5 x 7.5 x 3.5
	Shear	10 x 5.4 x 0.6	8.5 x 4.9 x 0.6	7.5 x 7.5 x 3.5

2.3.2 Adhesive 1

Adhesive 1 was a Titebond Heavy Duty solvent based construction adhesive (SBCA), a synthetic elastomeric polymer, manufactured and provided by Franklin International. The adhesive is believed to be a styrene-butadiene-styrene block copolymer.

2.3.3 Adhesive 2

Adhesive 2 was a two-component low foaming emulsion polymer isocyanate (EPI), manufactured and provided by Franklin International. It consisted of a hardener (Hardener 200) and a resin (ReacTITE EP-925). The mixture was composed of a 15:100 ratio of hardener to resin by weight, per manufacturer specifications. The resin was in the polyvinyl acetate emulsion adhesive family and the hardener was in the polymeric MDI family.

2.3.4 Nails

To provide a baseline that the adhesive connections could be compared against, a commonly used, annularly threaded 3in pallet nail was used to secure the pallet components together. The specifications of the nail design are listed in **Table 3**. The Fastener Withdrawal Index and Fastener Shear Index values were determined by following the guidelines of ASTM F680 (ASTM, 2017).

Table 3. Summary table of the average specifications of the pallet nails from measured values.

Nominal Fastener Length	**3.00 in.**
Wire Diameter	**0.135 in.**
Head Diameter	**0.285 in.**
Thread Length	**1.844 in.**
Thread-Crest Diameter	**0.144 in.**
Number of Rings	**35.8**
MIBANT angle	**18 degree**
Fastener Withdrawal Index	**232.76**
Fastener Shear Index	**138.92**

2.3.5 Adhesive Application

Adhesive was applied in an excessive amount onto one of the components being glued (**Figure 13**). The solvent based construction adhesive (SBCA) was applied using a caulk gun to create multiple lines running perpendicular to the wood grain. The two-part emulsion polymer isocyanate (EPI) was applied by pouring a larger amount than needed on the area. A metal trowel was then used to spread the adhesive along the grain until it covered the whole cross section evenly (**Figure 14**). A ¼" x ¼" x ¼" square notched trowel was used for the SBCA, and a 3/16" x 5/32" small v notch trowel was used for the EPI. Once the adhesive was applied to the first wooden component, the second component of the sample was placed onto the first component. Adhesive that had been applied outside the lines of the cross section was wiped away prior to applying pressure. Once the samples were assembled, they were placed into a Lansmont squeezer (Lansmont Corp) equipped with a 5,000lb. load cell. Variable pressure, based on the experimental design, was applied for one hour. Adhesive squeeze out, which occurred during the pressure application, was left on the sample. A jig was used to apply pressure evenly and to prevent the movement of components during compression. The compressed samples cured for either 48 hours or a minimum of 7 days based on the experimental design. All samples were prepared and cured in a room temperature environment.

2.3.6 Nail Application

All components for nailed samples were predrilled in a consistent pattern using a drill press. To prevent splitting, a drill bit less than 90% of the diameter of the nail shank was used. The predrilling process had no effect on the strength of the connection according to the Wood Handbook section 8.2. After components were predrilled, all nails were hammered by hand. Components for the samples were held in place, during drilling and nailing, using clamps.

Figure 13. Example picture of the application of the two adhesives prior to spreading: (left) solvent based construction adhesive (SBCA), (right) emulsion polymer isocyanate (EPI).

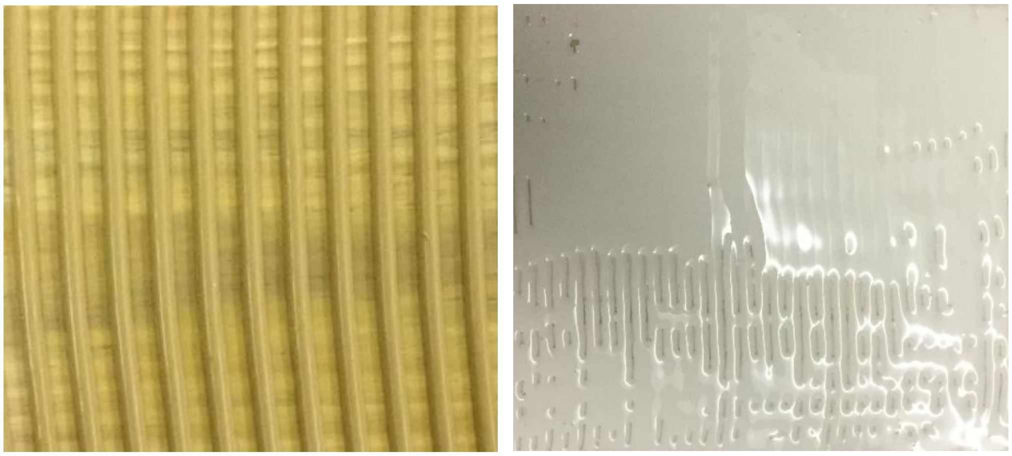


Figure 14. Example picture of the result of the spreading of the adhesive with a metal trowel along the grain covering cross section: (left) solvent based construction adhesive (SBCA), (right) emulsion polymer isocyanate (EPI).

2.3.7 Pallet Connection

The connections tested were between the lead top deckboard, the stringerboard, and the block at the corner of the pallet. This connection was selected because it is the connection that experiences the most damage due to handling from forklifts and pallet jacks. It has both perpendicular to the grain and parallel to the grain bonding which results in different strengths and both shear and tension stresses, which also occur in other connections in the pallet.

2.3.8 Sample Preparation for the Tension Perpendicular to the Grain Test

Samples simulating the connection between the lead top deckboard and stringerboard were assembled with components perpendicular to each other (**Figure 15**). There was a 1” overhang on all sides of the cross section.

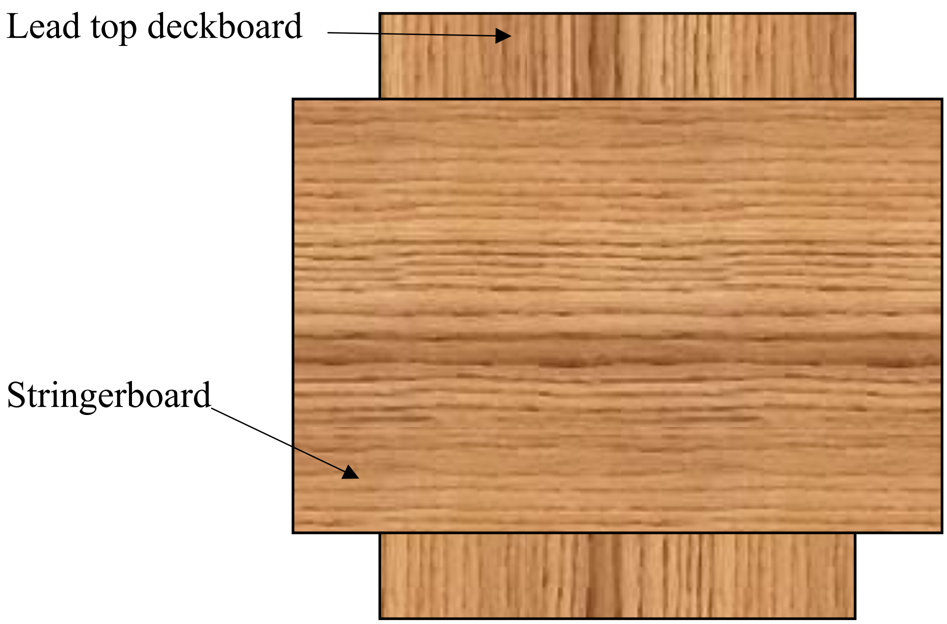


Figure 15. Placement of the components for the lead top deckboard and stringerboard connection used for the tension perpendicular test.

2.3.9 Sample Preparation for the Tension Parallel to the Grain Test

Samples simulating a stringerboard to block connection were assembled with both components parallel to each other (**Figure 16**).

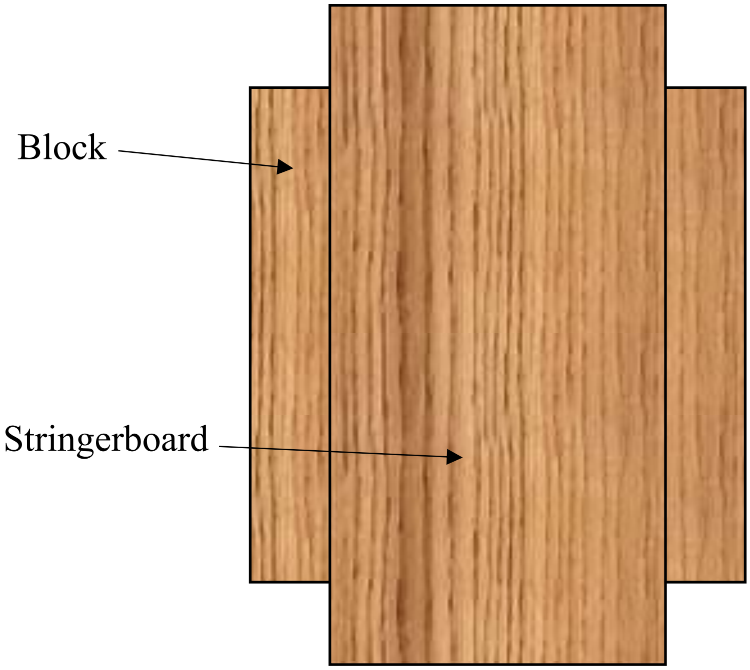


Figure 16. Placement of the components for the stringerboard and block connection used for the tension parallel test.

2.3.10 **Sample Preparation for the Shear Test**

Samples simulating the deckboard to stringerboard to block connection were assembled with the stringerboard component parallel to the block component and deckboard component perpendicular to the stringerboard component (**Figure 17**).

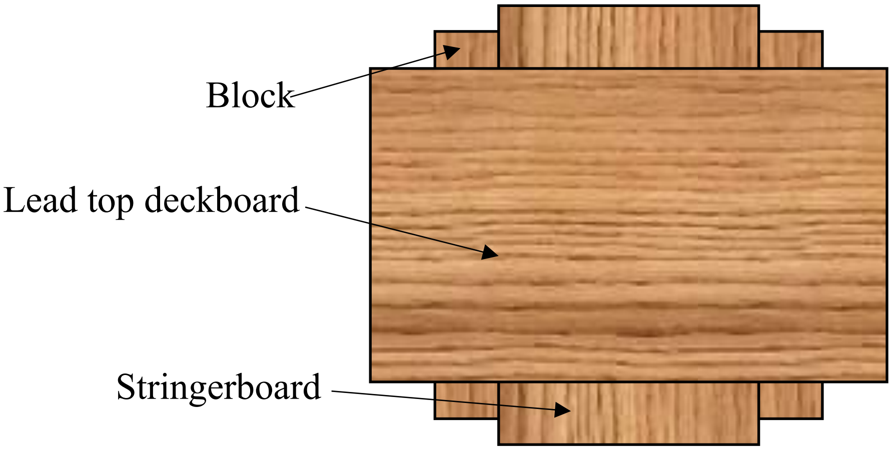
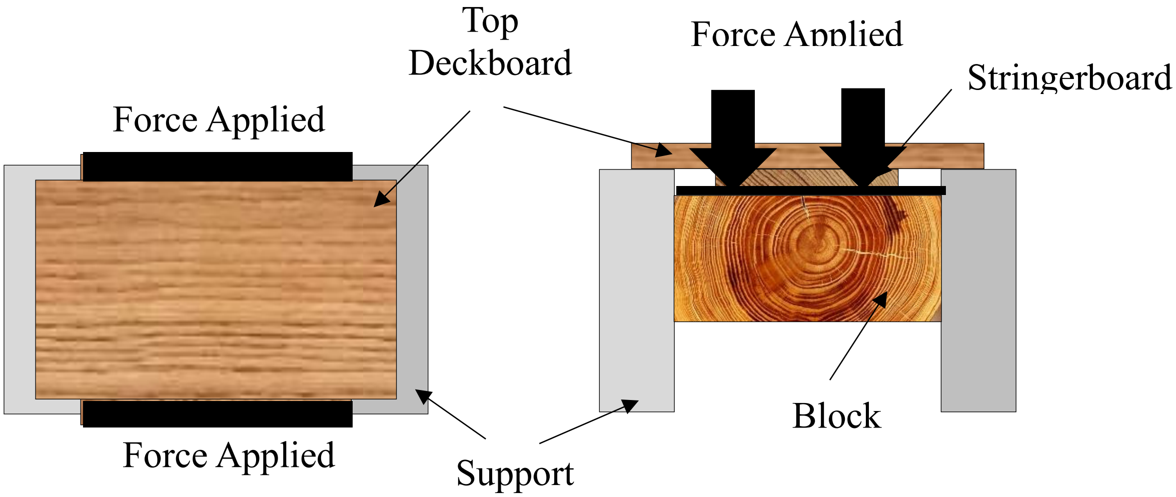


Figure 17. Placement of the components for the lead top deckboard, stringerboard, and block connection used for the shear strength test.

2.4 Methods

The standard test method for determining the strength of pallet joints, according to the guidelines of ISO 12777-3 (ISO, 2002) was used to measure the strength of the joints connected with nails and those connected with adhesives, in both tension and shear. A universal testing machine

(MTS model number B366731-01) equipped with a 25,000lbs. load cell (model number 661.21A-03) was used for testing all samples at a constant loading rate of 0.4in. per minute. The deformation of the connected components was measured by the cross-head movement of the tester. The load and deformation were recorded using an automatic data acquisition system. Percentage of wood failure was determined by a visual inspection of all samples after testing. The experimental setup for each of the different tests are presented in **Figure 18** to **Figure 23**.



Top View

Side View

Figure 18. Top (left) and side (right) view of experimental setup for testing nailed samples using a universal testing machine to determine the tension strength of the joint connection.

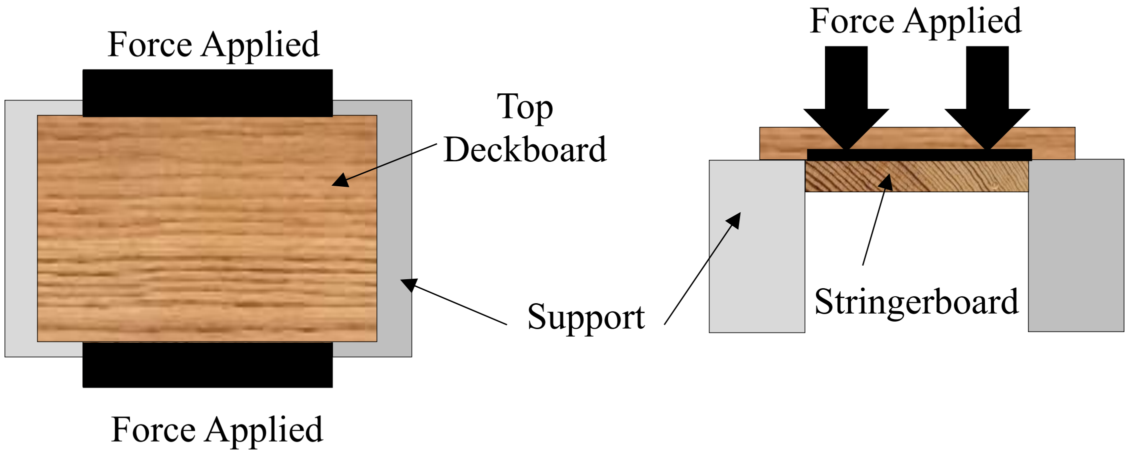


Figure 19. Top (left) and side (right) view of experimental setup for testing samples assembled with adhesive using a universal testing machine to determine the tension strength between the stringerboard and deckboard components.

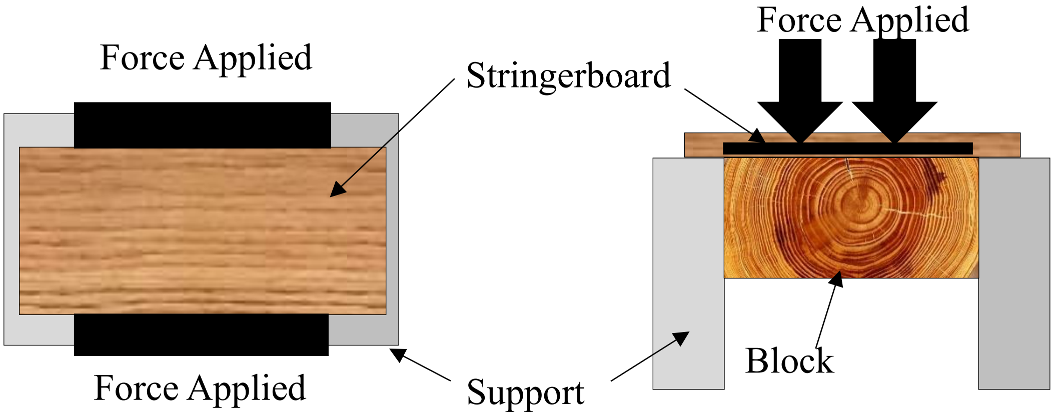


Figure 20. Top (left) and side (right) view of experimental setup for testing samples assembled with adhesive using a universal testing machine to determine the tension strength between the stringerboard and block components.

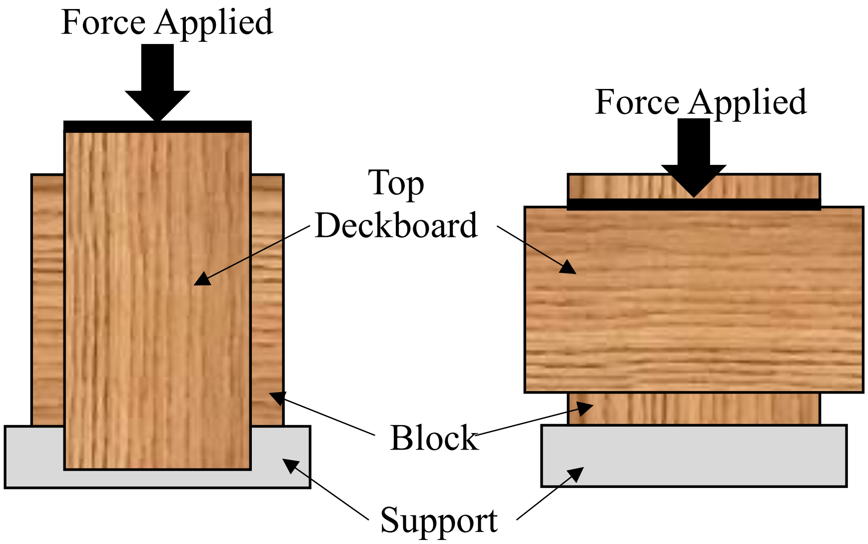


Figure 21. Front view of experimental setup for testing nailed samples using a universal testing machine to determine the shear strength of the joint connection.

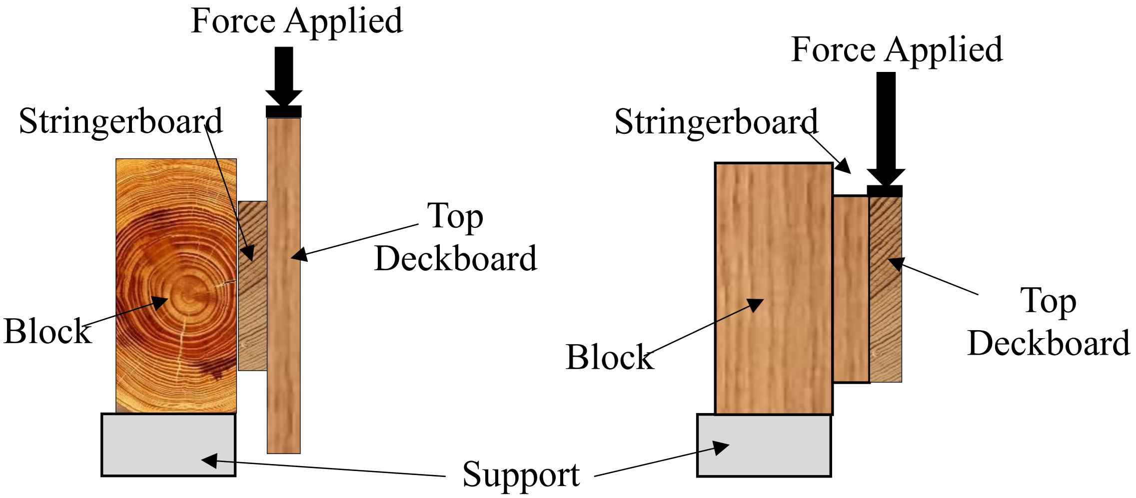


Figure 22. Side view of experimental setup for testing nailed samples using a universal testing machine to determine the shear strength of the joint connection.

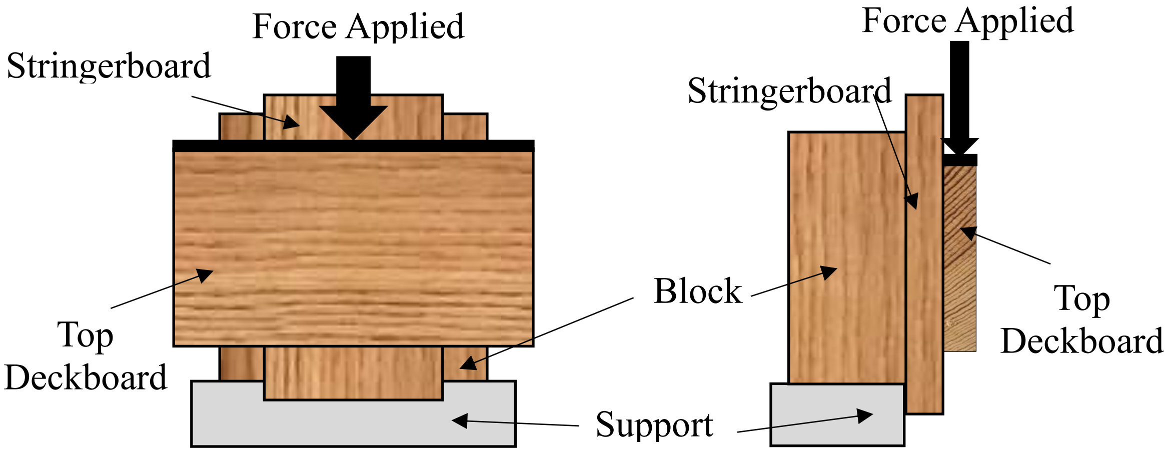


Figure 23. Front (left) and side (right) view of experimental setup for testing samples assembled with adhesive using a universal testing machine to determine the shear strength of the joint connection.

2.5 Experimental Design

The experimental design for the study is presented in **Table 4** and **Table 5**. The effects of the three treatments on the mechanical strength of each pallet connection were investigated. The three treatments included connection type, applied pressure, and curing time. The mechanical strength tested included the tension strength perpendicular to the grain, the tension strength parallel to the grain, and the shear strength of the connection. Pressures tested included 5, 25, 50, 75, 100, and 125 psi. The different curing times were either 48 hours or a minimum of 7 days. Twenty replicate tests were conducted for all experiments except for the experiments with a 48-hour curing time and the experiment testing the shear strength of the nailed connections.

Table 4. Effect of curing time during the tension test perpendicular to the grain.

Connection Type	Pressure	48 hours	7+ days
Solvent Based Construction Adhesive (SBCA)	5 psi	5 samples	20 samples
	25 psi	5 samples	20 samples
	50 psi	5 samples	20 samples
	75 psi	5 samples	20 samples
	100 psi	5 samples	20 samples
	125 psi	5 samples	20 samples

Table 5. Effect of the connection type based on the pressure applied.

Connection Type	Pre-Compression Pressure	Tension Strength Perpendicular to the Grain	Tension Strength Parallel to the Grain	Shear Strength
Nail	N/A	20 samples	20 samples	40 samples
Solvent Based Construction Adhesive (SBCA)	5 psi	20 samples	20 samples	20 samples
	25 psi	20 samples	N/A	N/A
	50 psi	20 samples	20 samples	20 samples
	75 psi	20 samples	N/A	N/A
	100 psi	20 samples	20 samples	20 samples
	125 psi	20 samples	N/A	N/A
Emulsion Polymer Isocyanate (EPI)	5 psi	20 samples	20 samples	20 samples
	25 psi	20 samples	N/A	N/A
	50 psi	20 samples	20 samples	20 samples
	75 psi	20 samples	N/A	N/A
	100 psi	20 samples	20 samples	20 samples
	125 psi	20 samples	N/A	N/A

2.6 Statistics

For all data sets the distribution was tested with a Shapiro-Wilk W goodness of fit test, with α set at 0.05. Various tests were also conducted to determine if the data had equal variances. These tests were O'Brien, Brown-Forsthe, Levene, Bartlett, and 2-sided F Test. All of the statistical analysis tests that were conducted are found in the Appendix.

If the data sets that compared two groups, i.e. data comparing samples tested after 48 hours to those tested after 7+ days, was found to have normal distribution and equal variances then a t-test was conducted. If the data was normally distributed but did not have equal variances, a t-test was still conducted, but it was set up assuming unequal variances. If the data was not normally distributed, then a Wilcoxon/Kruskal-Wallis test was conducted to determine whether or not both groups were significantly different.

For all data sets comparing multiple groups, if the data was normally distributed and had equal variances, an ANOVA test was conducted with α of 0.05 to determine if any group was significantly different. If there was a significant difference a Tukey’s HSD test was conducted to determine which of the groups were different. If the data was normally distributed but did not have equal variances, then a Welch’s test was conducted, in replacement of the ANOVA test, also with α of 0.05. If there was a difference, a Tukey’s HSD test was conducted. If the data was not normally distributed, with equal or unequal variances, a nonparametric Wilcoxon/Kruskal-Wallis test, with α of 0.05, was conducted to determine if there was a difference. If the Wilcoxon test determined at least one group was significant different, a nonparametric comparison test for each pair was conducted using the Wilcoxon method. This showed which of the groups were different from each other.

2.7 Results and Discussion

2.7.1 Effect of curing time on the tensile strength perpendicular to the grain of the connection at different pressures using a solvent based construction adhesive

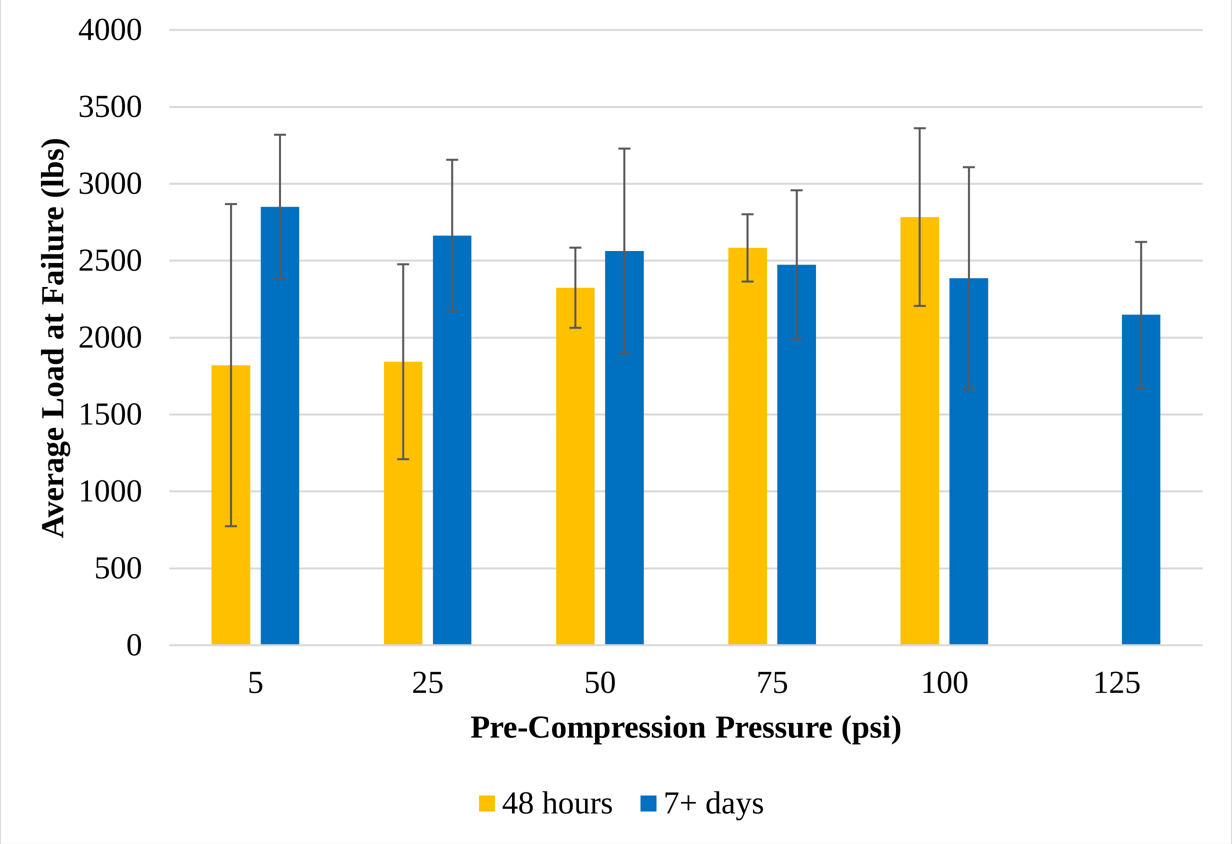
The first samples were made using the solvent based construction adhesive (SBCA). The manufacturer, Franklin International, specified that their adhesives would cure to 90% strength in 48 hours and to 100% strength in 7-10 days after being compressed for 1 hour under 100 psi pre-compression pressure. As the first phase of the testing, five samples were made using pre-compression pressures ranging from 5 to 100 psi. Then the tensile strength between the stringerboard and deckboard connection was measured after 48 hours. The results are presented in **Figure 24** and **Table 6**.

As compression pressure increased the average tensile strength of the connection increased as well. In addition, lower standard deviation values were observed when greater compression pressures were used (**Figure 24**). This might be attributed to the change in the bond line thickness. At lower pre-compression pressures less adhesive was squeezed out and a thicker bond line was created. With this thicker bond line there was more adhesive remaining between the components to cure which would take longer resulting in partially cured connections and larger variation in the results.

Due to the large variances in the results of the 48-hour pressure study, the time between pressure application and testing was increased to a minimum of 7 days to allow all samples to cure 100% and reach their full strength before testing. Since average tensile strength perpendicular to the grain increased as the pre-compression pressure increased during the 48 hours study, a 125 psi pre-compression pressure level was added to the study. The sample size was also increased to 20 samples per group to follow the ISO standard 12777-3 (ISO, 2002). The results of both the 48 hours and 7+ day study are presented in **Figure 24** and **Table 6**.

While average tensile strength perpendicular to the grain increased with increasing pressure for the samples that were tested after 48 hours, the opposite effect was seen in the samples tested after 7+ days. For the samples that were left to cure for 7+ days, standard deviation was more consistent between the groups when compared to the groups of samples tested after 48 hours. There was a statistically significant difference between them, with the samples tested after 7+ days failing at higher loads.

Samples pre-compressed under 5 psi and 25 psi and cured for 7+ days exhibited a statistically greater tensile strength than those tested after 48 hours. However, there was no statistically significant difference found for samples compressed under 50, 75, and 100 psi and cured for 7+ days when compared to the samples compressed under the same amounts and tested after 48 hours.



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 24. Average tensile strength for stringerboard to deckboard connection using a solvent based construction adhesive tested 48 hours and 7+ days after production

Table 6. Summary table for average tensile strength for stringerboard to deckboard connection using a solvent based construction adhesive tested 48 hours and 7+ days after production

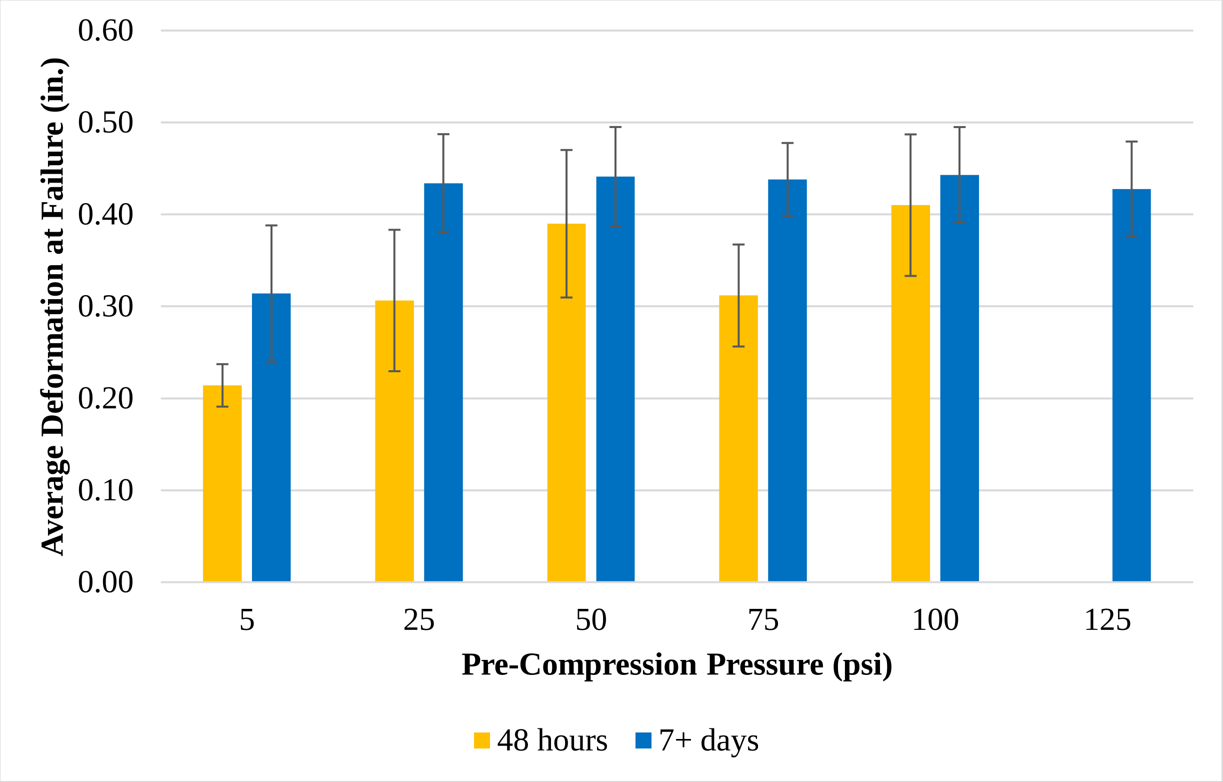
Pre-Compression Pressure (psi)	Average Tensile Strength Perpendicular to the Grain (lbs.)				T-Test (prob µ1 < µ2)	Wilcoxon Test
	48 Hours		7+ Days			
	Mean	COV	Mean	COV		
5	1,821	58%	2,851	16%		µ1 < µ2
25	1,843	34%	2,663	18%	0.0022	
50	2,324	11%	2,563	26%	0.2219	
75	2,583	8%	2,473	20%	0.6852	
100	2,784	21%	2,386	30%	0.8665	
125	- - -	- - -	2,148	22%	- - -	- - -

*Note: µ1 = average tensile strength for samples tested after 48 hours while µ2 = average tensile strength for samples tested after 7+ days

The average deformation of the connection at failure increased with increasing pre-compression pressure for samples tested after 48 hours, Meanwhile the average deformation for samples tested after 7+ days increased from 5psi to 25psi, but it did not appear to change above 25psi (**Figure 25**). Deformation at failure data for samples tested after 48 hours and after 7+ days can be seen in **Table 7.** There was a statistically significant difference between samples tested after 48 hours and those tested after 7+ days that were compressed under 5, 25, and 50 psi, with samples tested after 7+ days having a significantly larger average amount of deformation at failure. Samples pre-compressed under 75 psi and100 psi were not significantly different when tested after 48 hours or after 7+ days (production **Table 9)**.

The energy it took to break the connection was calculated using data up to the highest load, rather than at total failure or at a certain deflection due to some samples breaking apart at the highest load while others continuing to separate past it. As pre-compression increased, there was no clear trend for how much average energy it took to break the samples using different pre-compression pressures for both samples tested 48 hours and those tested after 7+ days. While there was no clear trend overall, there were high variations observed in the average tensile strength of samples pre-compressed under 5 psi and tested after 48 hours and high variations were also observed in the average amount of energy until failure as well. There was a statistically significant difference in the samples pre-compressed under 5, 25, and 75 psi between those tested after 48 hours to those tested after 7+ days. There was no significant difference between both groups for samples that were pre-compressed under 50 psi and 100 psi (

Table 8). Increasing the curing time before testing resulted in a higher average amount of energy under all pre-compression pressures to reach failure, which is beneficial in pallet connections.



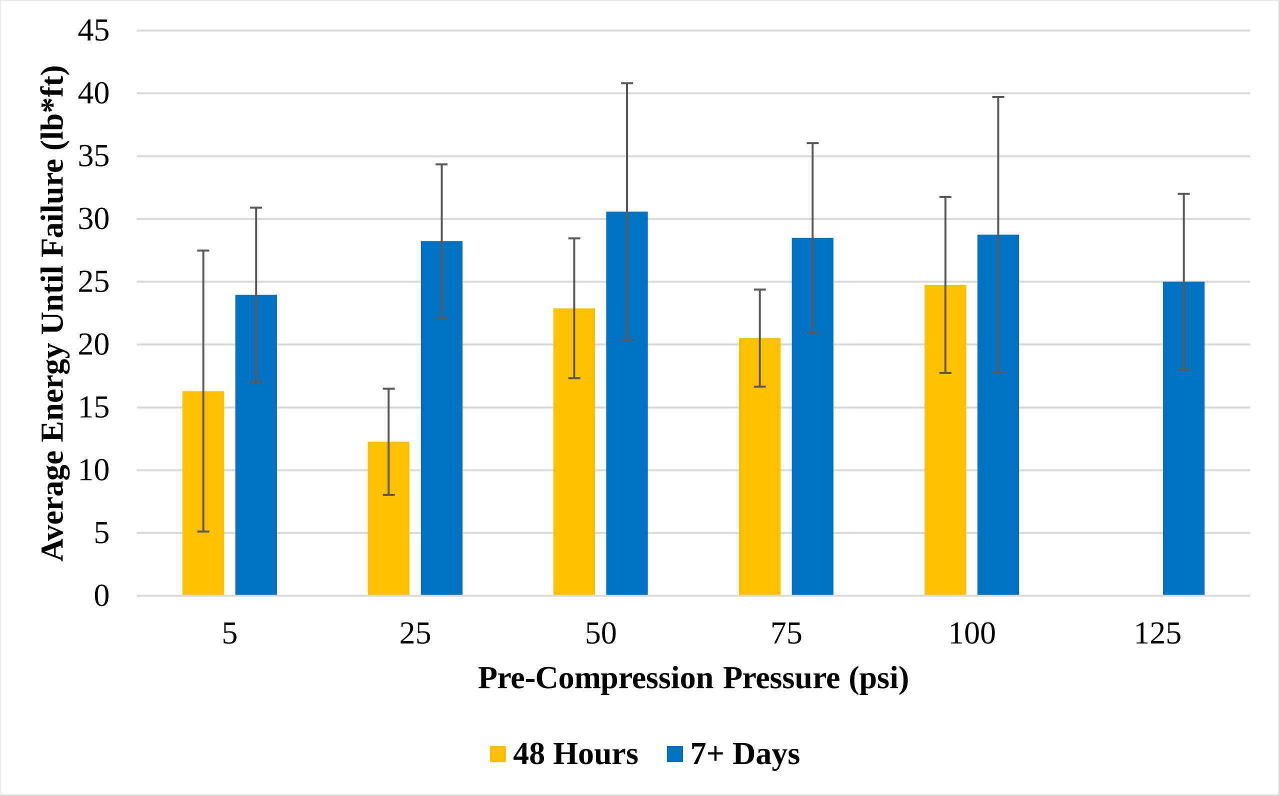
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 25. Average deformation at failure for stringerboard to deckboard connection using a solvent based construction adhesive tested 48 hours and 7+ days after production

Table 7. Summary table for average deformation at failure for stringerboard to deckboard connection using a solvent based construction adhesive 48 hours and 7+ days after production

Pre-Compression Pressure (psi)	**Average Deformation at Failure (in.)**				**T-Test (prob μ1 < μ2)**	**Wilcoxon Test**
	48 Hours		**7+ Days**			
	Mean	**COV**	**Mean**	**COV**		
5	0.21	11%	0.31	24%	0.0042	
25	0.31	25%	0.43	12%		μ1 < μ2
50	0.39	21%	0.44	12%	0.0497	
75	0.31	18%	0.44	9%		μ1 < μ2
100	0.41	19%	0.44	12%	0.1267	
125	- - -	- - -	0.43	12%	- - -	- - -

*Note: μ1 = average deformation at failure for samples tested after 48 hours while μ2 = average deformation at failure for samples tested after 7+ days



Note: Each error bar is constructed using 1 standard deviation from the mean

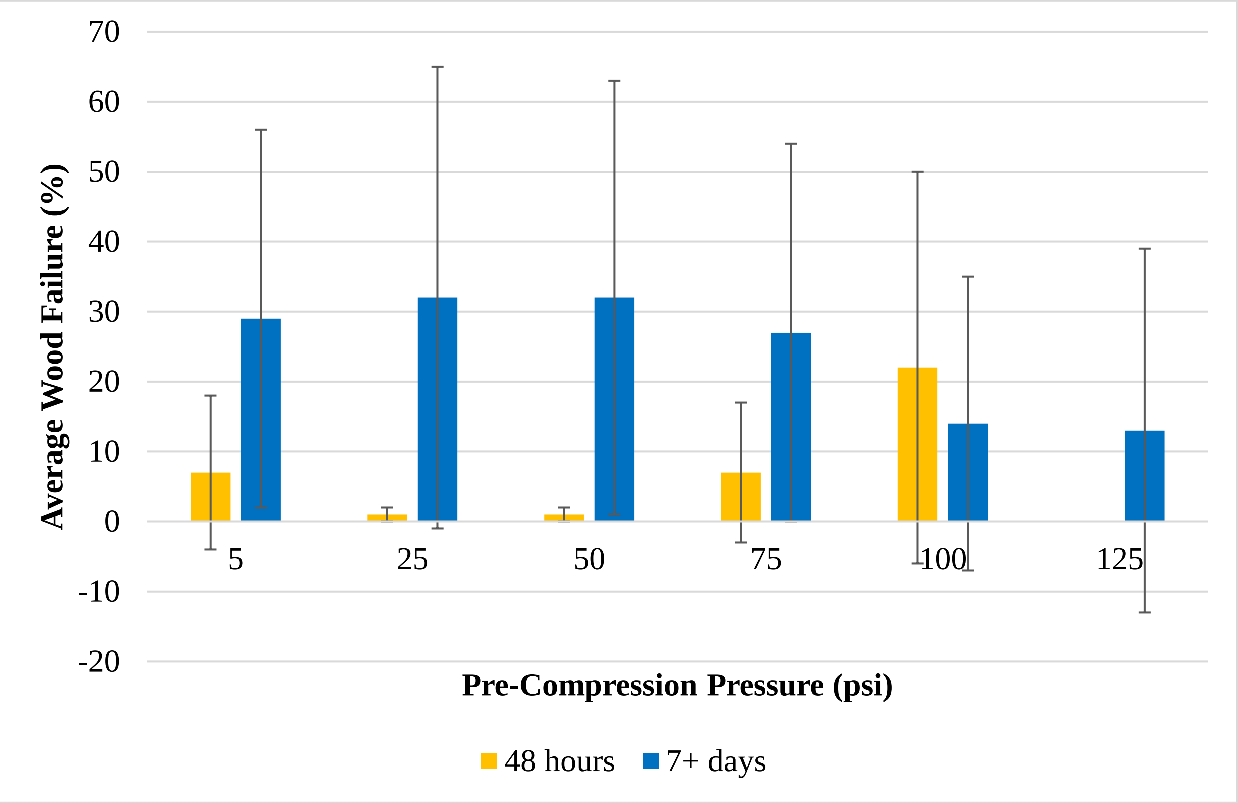
Figure 26 Average energy up to maximum load for stringerboard to deckboard connections tested in tension made under various pressures with a solvent based construction adhesive and tested 48 hours and 7+ days after production

Table 8. Summary table for average energy for failure for stringerboard to deckboard connection using a solvent based construction adhesive tested 48 hours and 7+ days after production

Pre-Compression Pressure (psi)	**Average Energy (ft-lb)**				**T-Test (prob µ1 < µ2)**	**Wilcoxon Test**
	48 Hours		**7+ Days**			
	Mean	**COV**	**Mean**	**COV**		
5	16	69%	24	29%	0.0298	
25	12	34%	28	22%	<0.0001	
50	23	24%	31	33%	0.0626	
75	21	19%	28	27%	0.0189	
100	25	28%	29	38%		µ1 = µ2
125	- - -	- - -	25	27%	- - -	- - -

*Note: µ1 = average deformation at failure for samples tested after 48 hours while µ2 = average deformation at failure for samples tested after 7+ days

The average wood failure for the tested samples was determined visually; the data is presented in **Figure 27** and **Table 9**. For samples tested after 48 hours, the average wood failure was lower when compared to samples tested after 7+ days for all pressures tested, except for the samples compressed under 100 psi, which can be attributed to the small sample size that was tested after 48 hours. Most samples tested after 48 hours had little-to-no wood failure, and once tested, still produced odor from the adhesive. Samples tested after 7+ days had more wood failure but had no odor; however, there was still a lot of variations in the amount of wood failure for all pre-compression pressures. Samples with higher pre-compression pressures had more wood failure in those tested after 48 hours, but the sample size was small and highly variable. Samples tested after 7+ days also had a high level of variations, but they showed a trend of a decreasing average amount of wood failure as the pre-compression pressure increased. Samples pre-compressed under 5, 25, and 50 psi and then tested after 7+ had statistically significant higher average amounts of wood failure than those tested after 48 hours. There was no significant difference between samples pre-compressed under 100 psi. Caution should be taken for the comparison of these two groups due to the small sample size for those tested after 48 hours. All statistical analysis tests can be found in Appendix A and images of wood failure can be seen in Appendix H.



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 27. Average wood failure for stringerboard to deckboard connections using a solvent based construction adhesive tested in tension perpendicular to the grain 48 hours and 7+ days after production

Table 9. Summary table for average wood failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension perpendicular to the grain 48 hours and 7+ days after production

Pre-Compression Pressure (psi)	Average Wood Failure (%)				Wilcoxon Test
	48 Hours		7+ Days		
	Mean	COV	Mean	COV	
5	7	156%	29	94%	µ1 < µ2
25	1	141%	32	103%	µ1 < µ2
50	1	91%	32	97%	µ1 < µ2
75	7	152%	27	98%	µ1 = µ2
100	22	131%	14	150%	µ1 = µ2
125	- - -	- - -	13	193%	- - -

*Note: µ1 = average deformation at failure for samples tested after 48 hours while µ2 = average deformation at failure for samples tested after 7+ days

2.7.2 Effect of pre-compression pressure on the strength of the connection

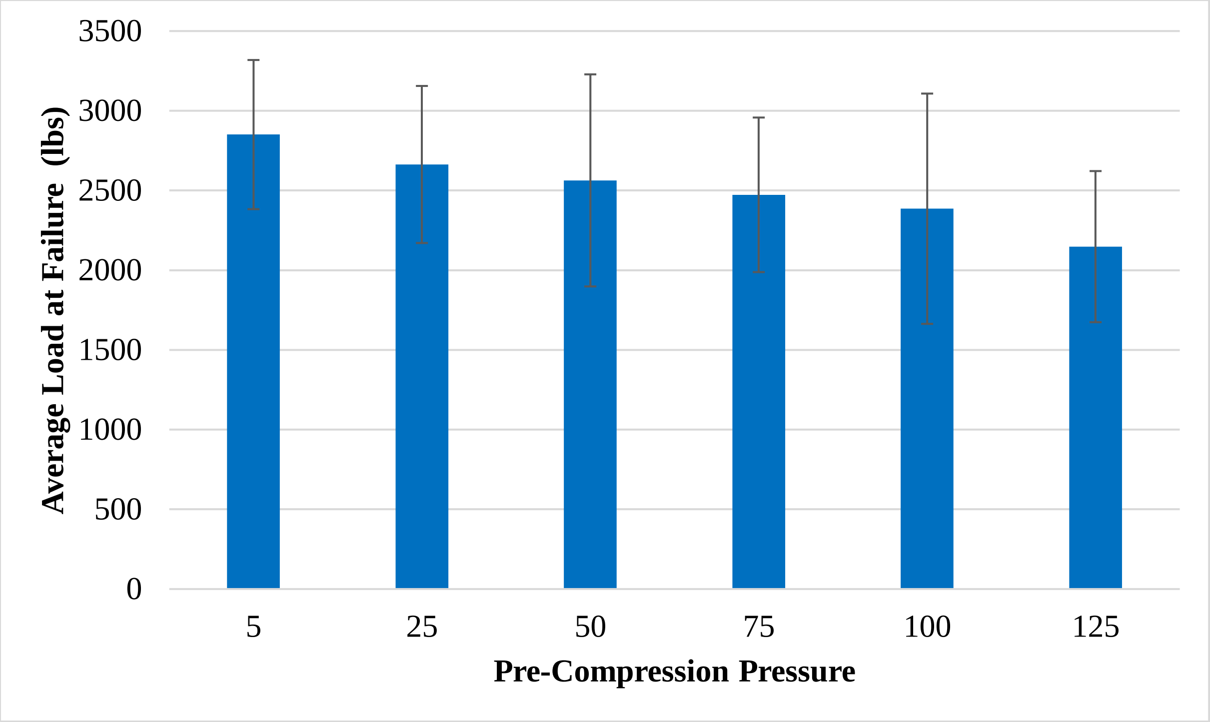
2.7.2.1 Effect of pre-compression pressure on the tensile strength perpendicular to the grain of the connection

These samples were made using both a solvent based construction adhesive (SBCA) and an emulsion polymer isocyanate (EPI) and pre-compressed under pressures ranging from 5 psi to 125 psi for one hour and tested after 7+ days to allow for 100% curing and full strength. Samples made with the SBCA showed decreasing tensile strength as the pre-compression pressure increased, with samples pre-compressed under 5 psi having the highest average tensile strength (**Table 10**). There was a significant difference in tensile strength between the samples made using 5psi and those made with 125 psi pre-compression pressure. This showed that pressure causes a significant decrease in strength, however the change was not statistically significant with each increasing level of pre-compression pressure tested. This decrease in strength could be attributed to the thinner bond line, and the larger amount of squeeze out as the pre-compression pressure was increased. The results of the data from samples made with the SBCA and tested in tensile strength bonded perpendicular to grain can be seen in **Table 10** and **Figure 28**.

Table 10. Summary table for average tensile strength for stringerboard to deckboard connection using a solvent based construction adhesive (SBCA) and an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

Pre-Compression Pressure (psi)	**Average Tensile Strength Perpendicular to the Grain (lbs.)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Tukey's HSD***	**Mean**	**COV**	**Tukey's HSD***
5	2,851	16%	A	2,355	20%	a
25	2,663	18%	AB	2,314	19%	a
50	2,563	26%	AB	2,484	20%	a
75	2,473	20%	AB	2,165	15%	a
100	2,386	30%	AB	2,329	27%	a
125	2,148	22%	B	2,139	23%	a

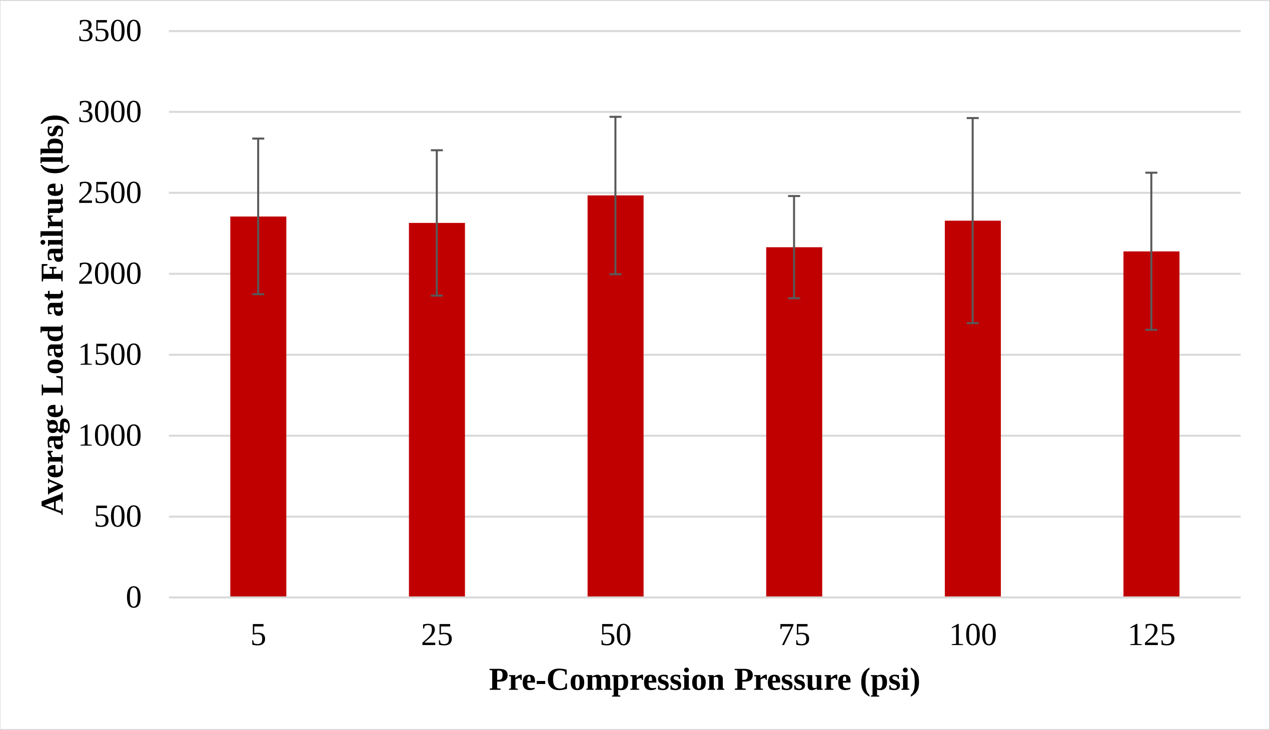
*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 28. Average tensile strength for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension perpendicular to the grain 7+ days after production

Samples made with the two component EPI did not show a clear trend as pre-compression pressure increased as did the samples made using the SBCA (**Figure 29**), however, both adhesives had an average tensile strength of over 2,000 lbs. for all pre-compression pressures tested (**Table 10)**). There was no statistically significant difference between groups made with the two component EPI using different pre-compression pressures. The average tensile strength of samples tested after 7+ days was not affected by a change in pre-compression pressure. This could be because the adhesive had a low viscosity which lead to a thin bond line regardless of the pre-compression pressure applied.



Note: Each error bar is constructed using 1 standard deviation from the mean

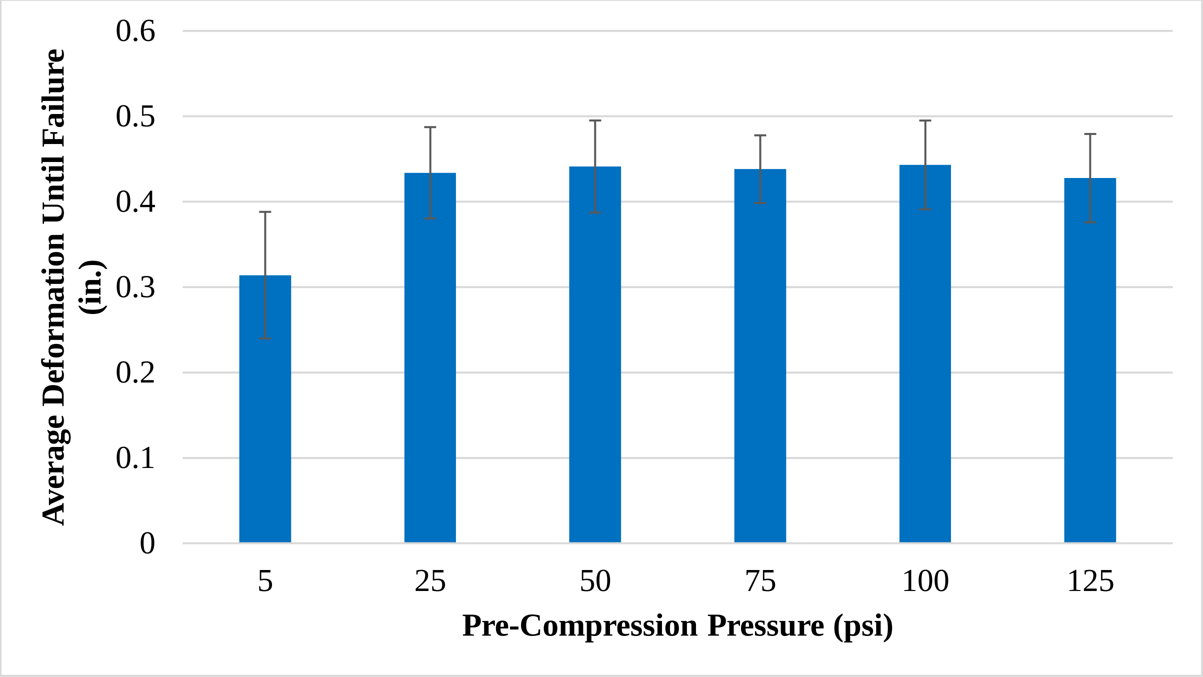
Figure 29. Average tensile strength for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

There was no difference in deformation at failure between 25 and 100 psi pressure after 7 days using the SBCA, and samples pre-compressed under 5 psi had lower deformation at failure. The results are in **Figure 30** and in **Table 11**. The lower deformation at failure for samples pre-compressed under 5 psi meant that those samples resisted deformation significantly less than the others and failed faster, despite on average failing at higher loads.

Table 11. Summary table for average deformation for stringerboard to deckboard connection using a solvent based construction adhesive (SBCA) and an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

Pre-Compression Pressure (psi)	**Average Deformation at Failure (in.)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon**	**Mean**	**COV**	**Wilcoxon**
5	0.31	24%	A	0.21	14%	a
25	0.43	12%	B	0.22	24%	a
50	0.44	12%	B	0.33	21%	b
75	0.44	9%	B	0.27	17%	b
100	0.44	12%	B	0.27	28%	b
125	0.43	12%	B	0.29	21%	b

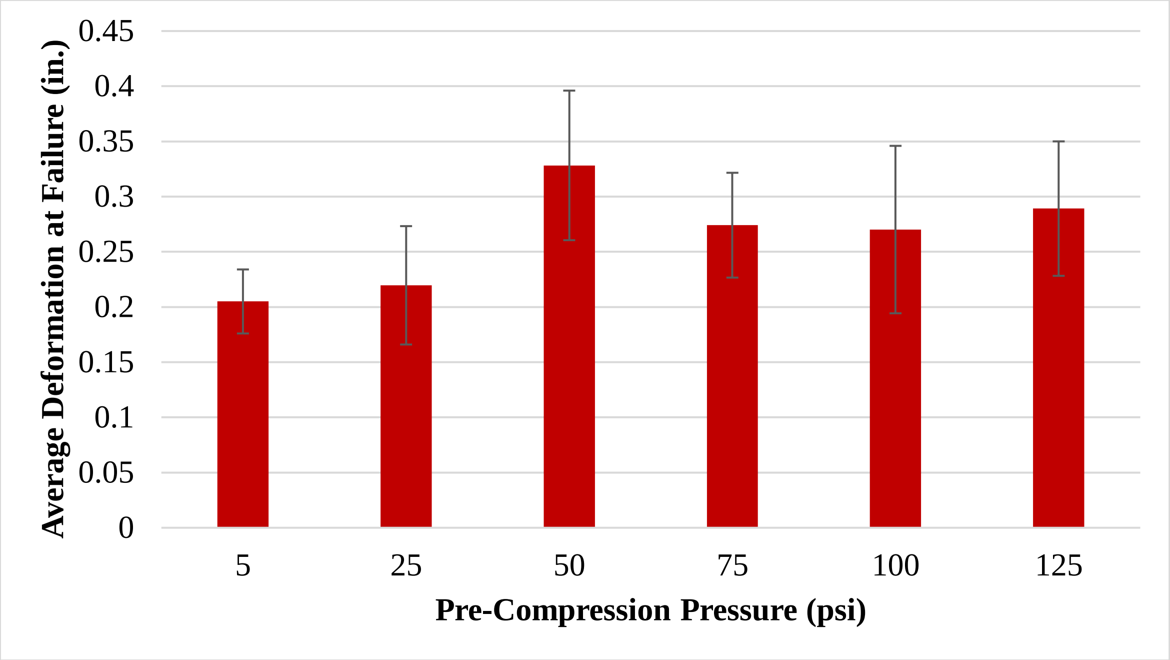
*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 30. Average deformation at failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension perpendicular to the grain 7+ days after production

Deformation at failure for samples made with the EPI, bonded perpendicular to grain, and tested 7+ days after testing, showed an increasing average deformation at failure as the pre-compression pressure increased (**Figure 31** and **Table 11**), but were lower than samples made with the SBCA for all pre-compression pressures. The average samples pre-compressed under 5 and 25 psi made with the two component EPI were not statistically different from each other but were significantly less than samples pre-compressed under 50 psi and higher. There was no significant difference for samples pre-compressed from 50 psi to 125 psi.



Note: Each error bar is constructed using 1 standard deviation from the mean

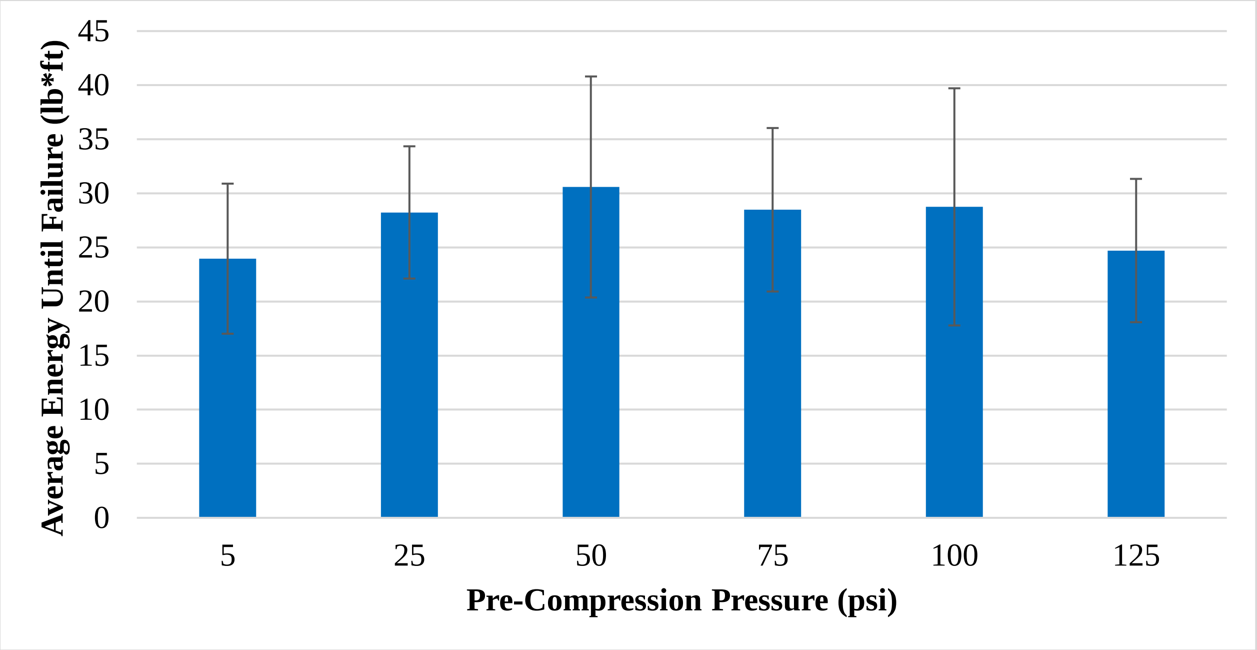
Figure 31. Average deformation at failure for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

For samples made with the SBCA, there was some increase in average energy until failure as pre-compression pressure increased from 5psi to 50psi; however, average energy started to decrease after pre-compression pressure increased to 75psi and higher (**Figure 32**). The energy causing failure for samples pre-compressed under 5psi was significantly lower than samples pre-compressed with 25psi and 50psi. This lower energy until failure for samples pre-compressed under 5psi reflects the lower deformation at failure despite also failing at higher loads. Meanwhile, the energy causing failure for samples pre-compressed using 5psi was not statistically different from that of samples pre-compressed using 75psi or higher pre-compression pressure (**Table 12**Error! Not a valid bookmark self-reference.).

Samples made with the two component EPI exhibited a lower average energy until failure than samples made with the SBCA at all pre-compression pressures, as shown in Table 3. This is reflective of the lower deformation at failure despite samples made with both adhesives having high average loads at failure. Overall, there was no change in average energy until failure as pressure increased (**Figure 33**). However, samples pre-compressed under 50psi did fail at higher average energy (**Table 12Error! Not a valid bookmark self-reference.**). There was no statistically significant difference for energy until failure at different pre-compression pressures, except for samples pre-compressed under 50psi. These had a significantly higher energy until failure when compared to all other groups. Samples pre-compressed at 50 psi failed at a higher average deformation and at higher force than samples pre-compressed under other pressures. This is why there was higher energy until failure for that group when compared to all other groups.

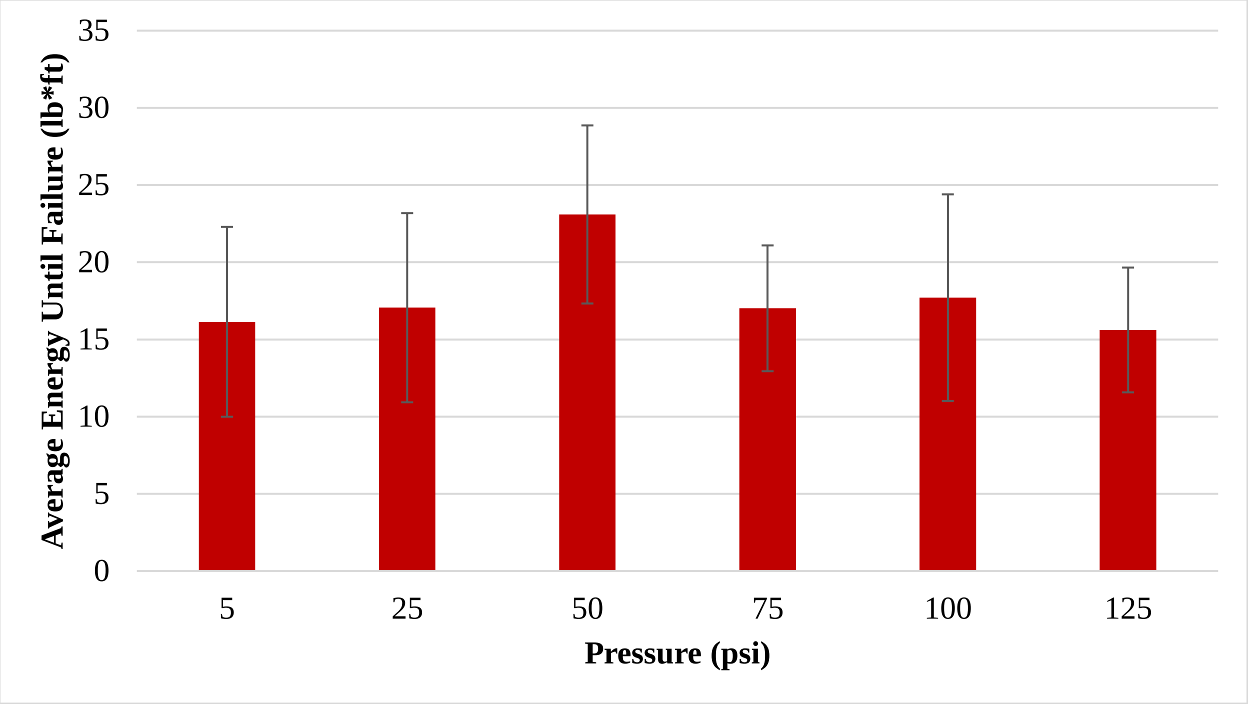
Table 12. Summary table for average energy until failure for stringerboard to deckboard connection using a solvent based construction adhesive and an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

Pre-Compression Pressure (psi)	**Average Energy until Failure (ft-lb)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon**	**Mean**	**COV**	**Wilcoxon**
5	24	29%	A	16	38%	b
25	28	22%	B	17	36%	b
50	31	33%	B	23	25%	a
75	28	27%	AB	17	24%	b
100	29	38%	AB	18	38%	b
125	25	27%	AB	16	26%	b



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 32. Average energy at failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension perpendicular to the grain 7+ days after production



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 33. Average energy at failure for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

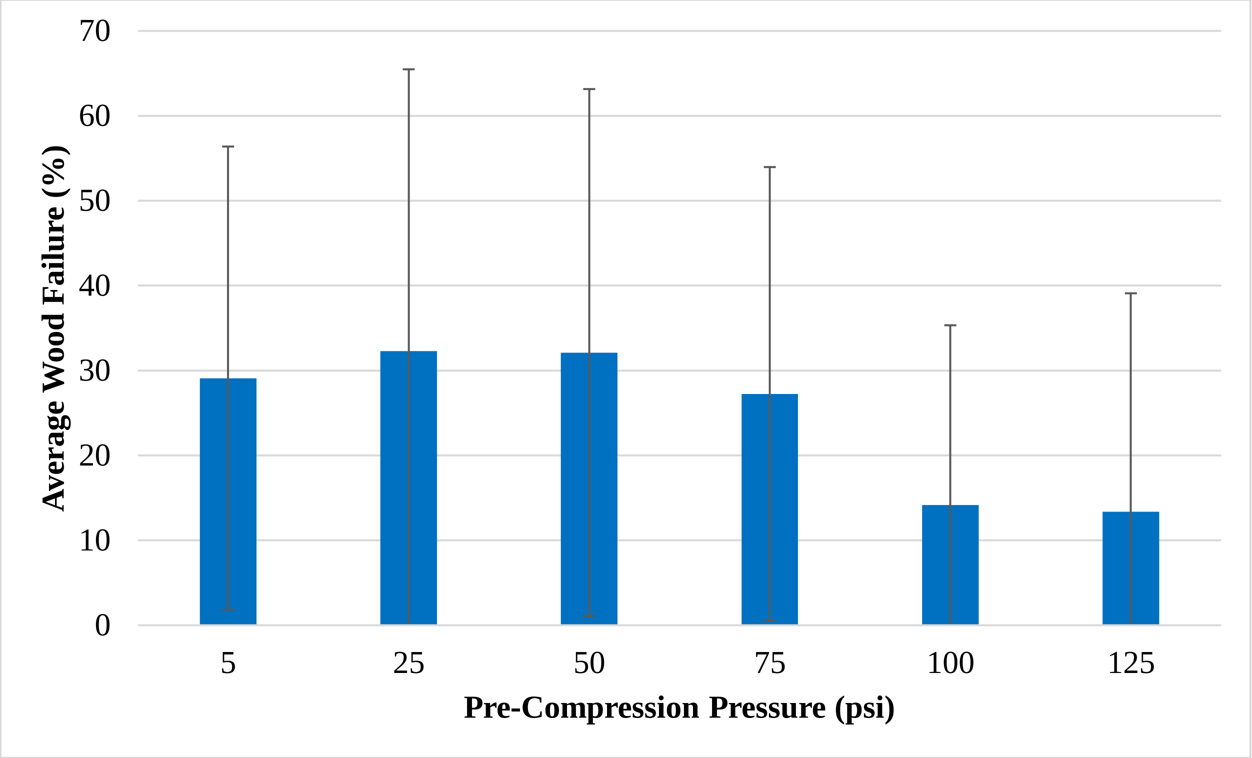
Wood failure for samples made with the SBCA, bonded perpendicular to grain, and tested 7+ days after testing, exhibited a large amount of variations in all pre-compression pressures tested. There was a decrease in the average amount of wood failure as the pre-compression pressure increased, which can be seen in **Figure 34** and **Table 13.** Samples pre-compressed under 125 psi had significantly lower amount of wood failure than those pre-compressed under 50 psi and 75 psi.

Wood failure for samples made with the two component EPI adhesive, bonded perpendicular to grain, and tested 7+ days after testing, had higher average percentage of wood failure and less variation than samples made with the SBCA under the same conditions (**Figure 35** and **Table 13**. While there were significant differences between the groups, there was not a clear trend as pre-compression pressure increased. All statistical analysis tests can be found in Appendix B and images of wood failure can be seen in Appendix H.

Table 13. Summary table for average amount of wood failure for stringerboard to deckboard connection using a solvent based construction adhesive and an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

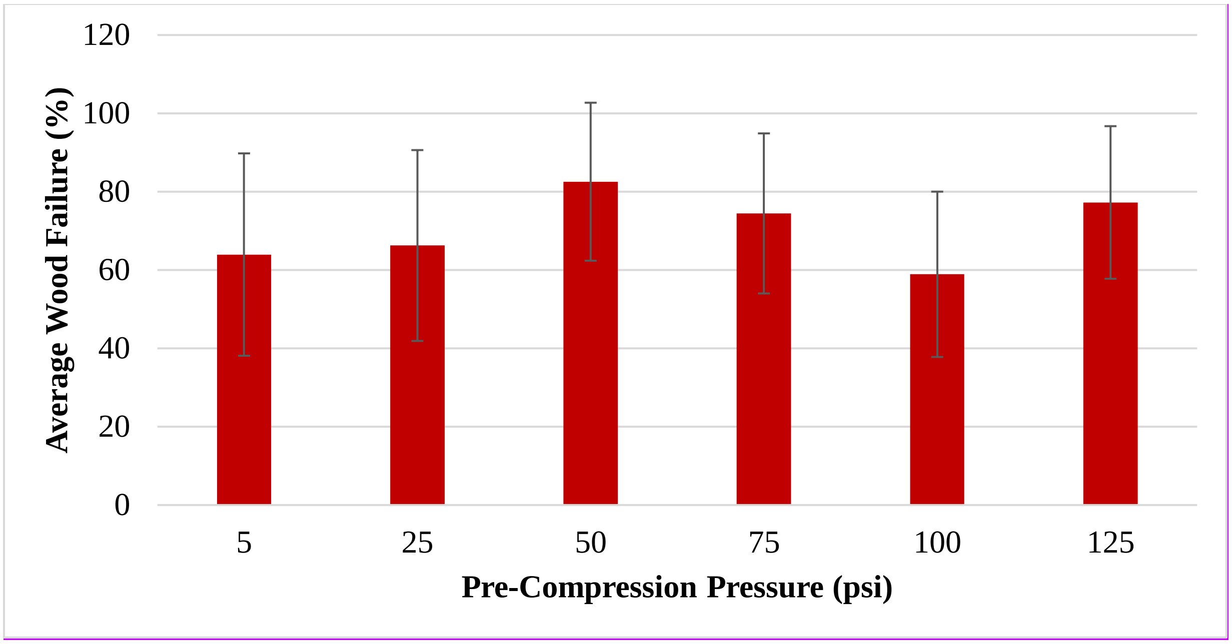
Pre-Compression Pressure (psi)	**Average Amount of Wood Failure (%)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon**	**Mean**	**COV**	**Wilcoxon**
5	29	94%	AB	64	40%	a
25	32	103%	AB	66	37%	ab
50	32	97%	B	83	24%	c
75	27	98%	B	74	27%	abc
100	14	150%	AB	59	36%	ab
125	13	193%	A	77	25%	abc

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 34. Average wood failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension perpendicular to the grain 7+ days after production



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 35. Average wood failure for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension perpendicular to the grain 7+ days after production

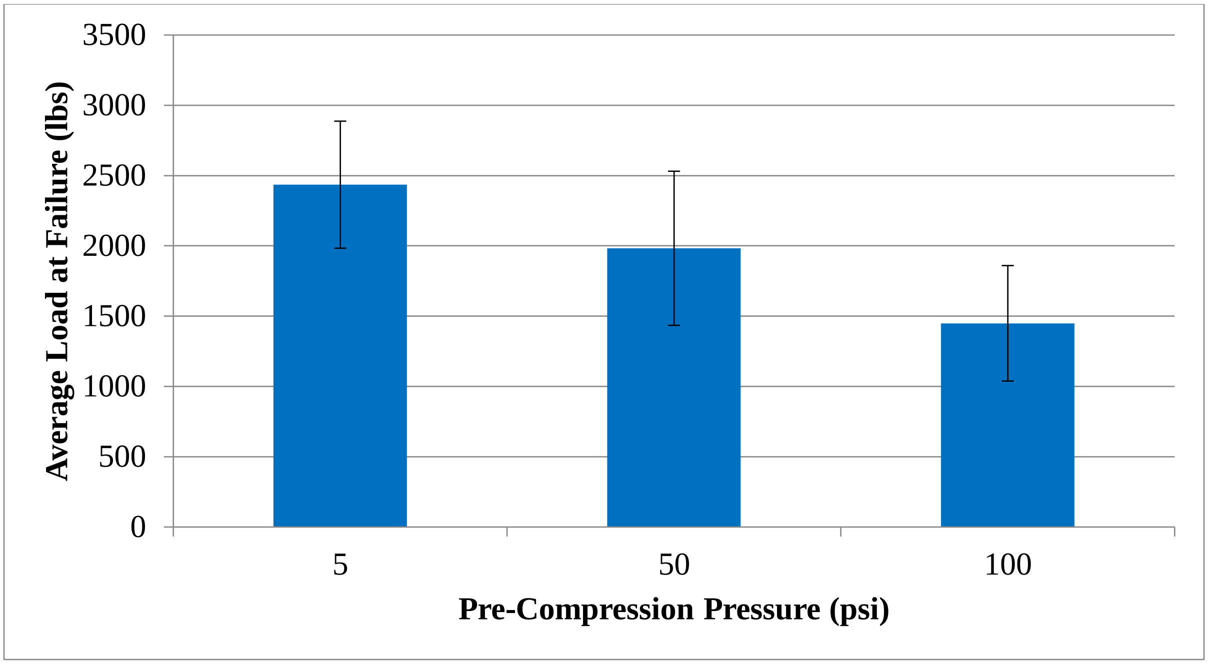
2.7.2.2 Effect of pre-compression pressure on the tensile strength parallel to the grain of the connection

The tensile strength of the samples bonded parallel to grain was tested on samples made with the SBCA and the two-component emulsion polymer isocyanate (EPI) (EPI). They were tested after 7+ days using pre-compression pressure of 5, 50, and 100 psi. For samples made with the SBCA as pre-compression pressure increased the average tensile strength decreased (**Figure 36**). All three groups were statistically significantly different from each other (**Table 14**). This decrease in strength could be due to the thicker bond lines left by smaller amounts of squeeze out that the samples at lower pressures experienced.

Table 14. Summary table for average tensile strength for stringboard to deckboard connection using a solvent based construction adhesive (SBCA) and an emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

Pre-Compression Pressure (psi)	**Average Tensile Strength Parallel to the Grain (lbs.)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Tukey's HSD***	**Mean**	**COV**	**Tukey's HSD***
5	2435	19%	A	1399	26%	a
50	1983	28%	B	1375	25%	a
100	1449	28%	C	1197	22%	a

*Note: Levels not connected by the same letter are significantly different

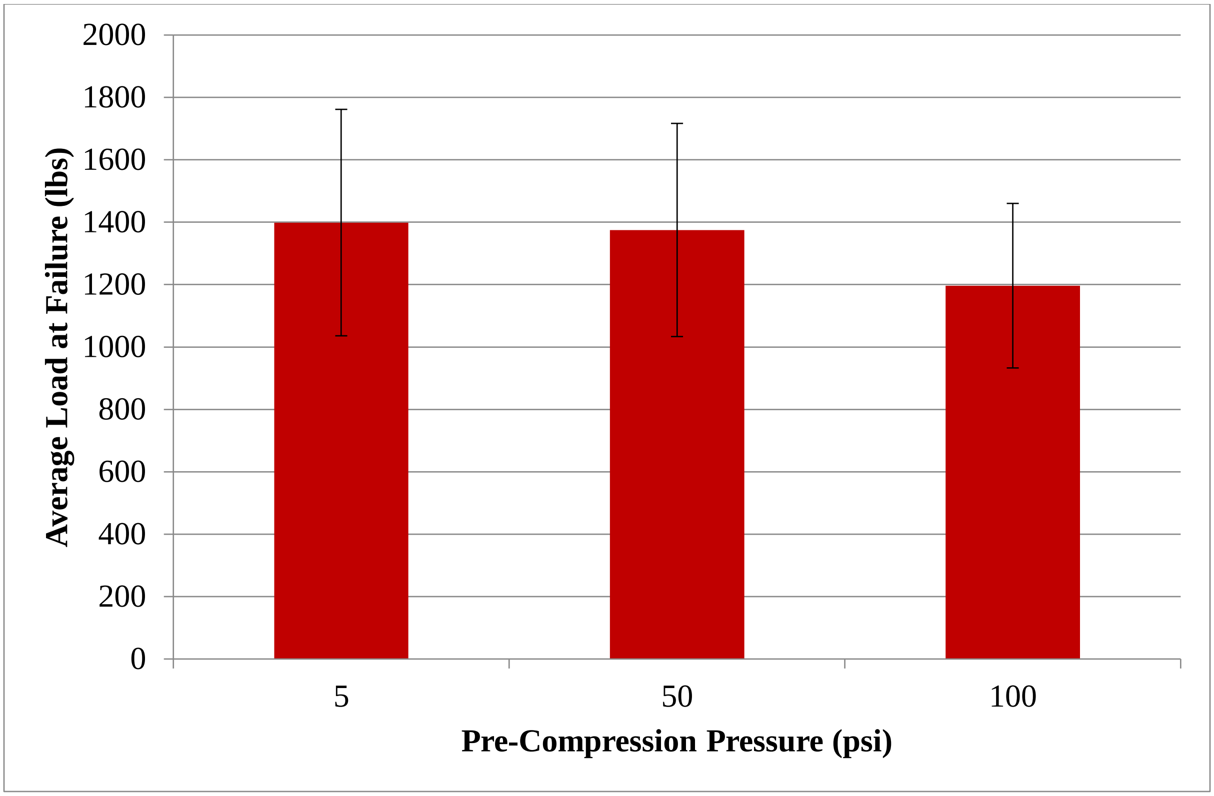


Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 36. Average tensile strength for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production

Samples made with the two component EPI adhesive also showed a decreasing trend in the average tensile strength as pre-compression pressure increased (**Figure 37**); however, this was not as drastic of a decrease as seen with the samples made with the SBCA. This difference could be due to the viscosity of the adhesive. The SBCA was highly viscous, and the two component EPI adhesive was not. There was no statistically significant difference of average tensile strength for samples pre-compressed at the different pressure levels when made with the two component EPI (**Table 14**). This could be due to the thin bondline that was achieved at all pre-compression pressures.

Reflecting the trend seen of the average tensile strength for samples made with the SBCA, there was a decrease in the average deformation at failure as pre-compression pressure increased (**Figure 38**). There was a statistically significant difference between the samples that were pre-compressed at 5 psi and those that were pre-compressed at 100 psi. This could be due to the higher pressure causing more squeeze-out and hence a thinner bondline.



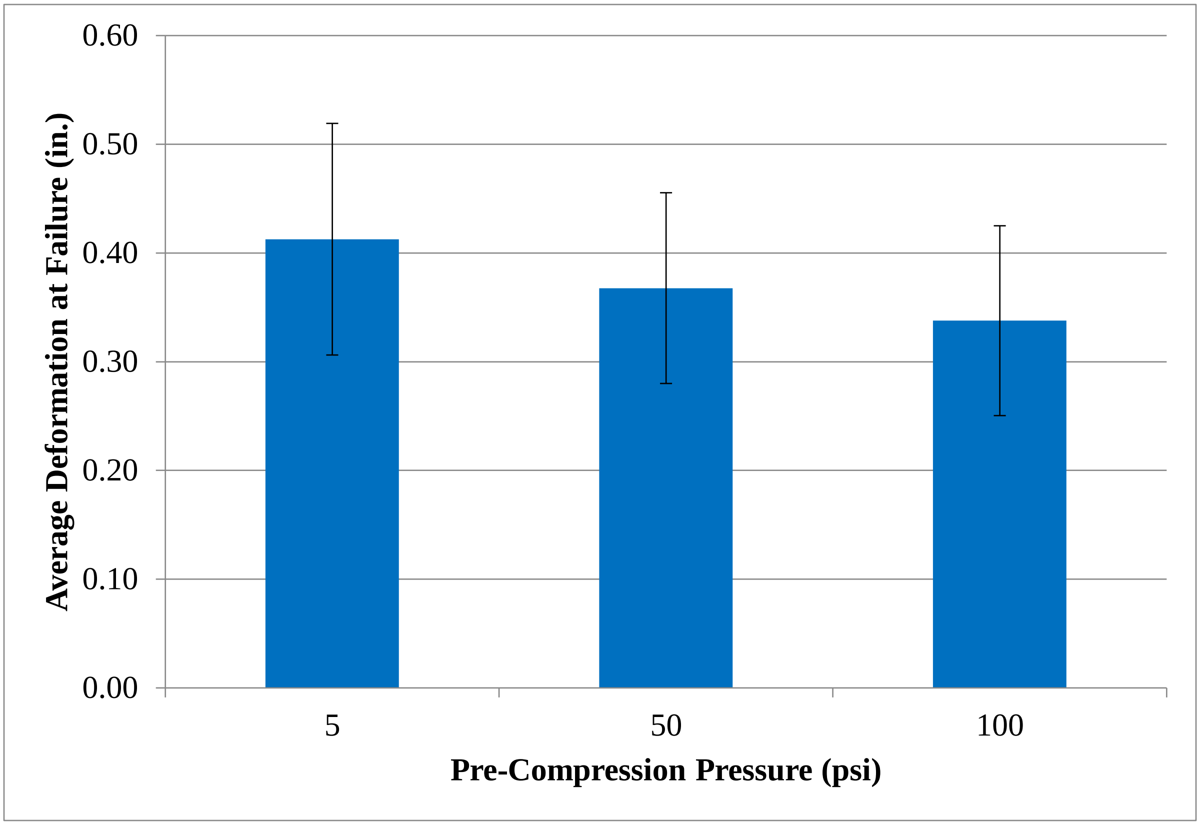
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 37. Average tensile strength for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

Table 15. Summary table for average deformation at failure for stringboard to deckboard connection using a solvent based construction adhesive and the two-component emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

Pre-Compression Pressure (psi)	Average Deformation at Failure (in.)					
	Solvent Based Construction Adhesive (SBCA)			Emulsion Polymer Isocyanate (EPI)		
	Mean	COV	Wilcoxon*	Mean	COV	Tukey's HSD*
5	0.41	26%	A	0.21	29%	a
50	0.37	24%	AB	0.23	43%	a
100	0.34	26%	B	0.40	27%	b

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

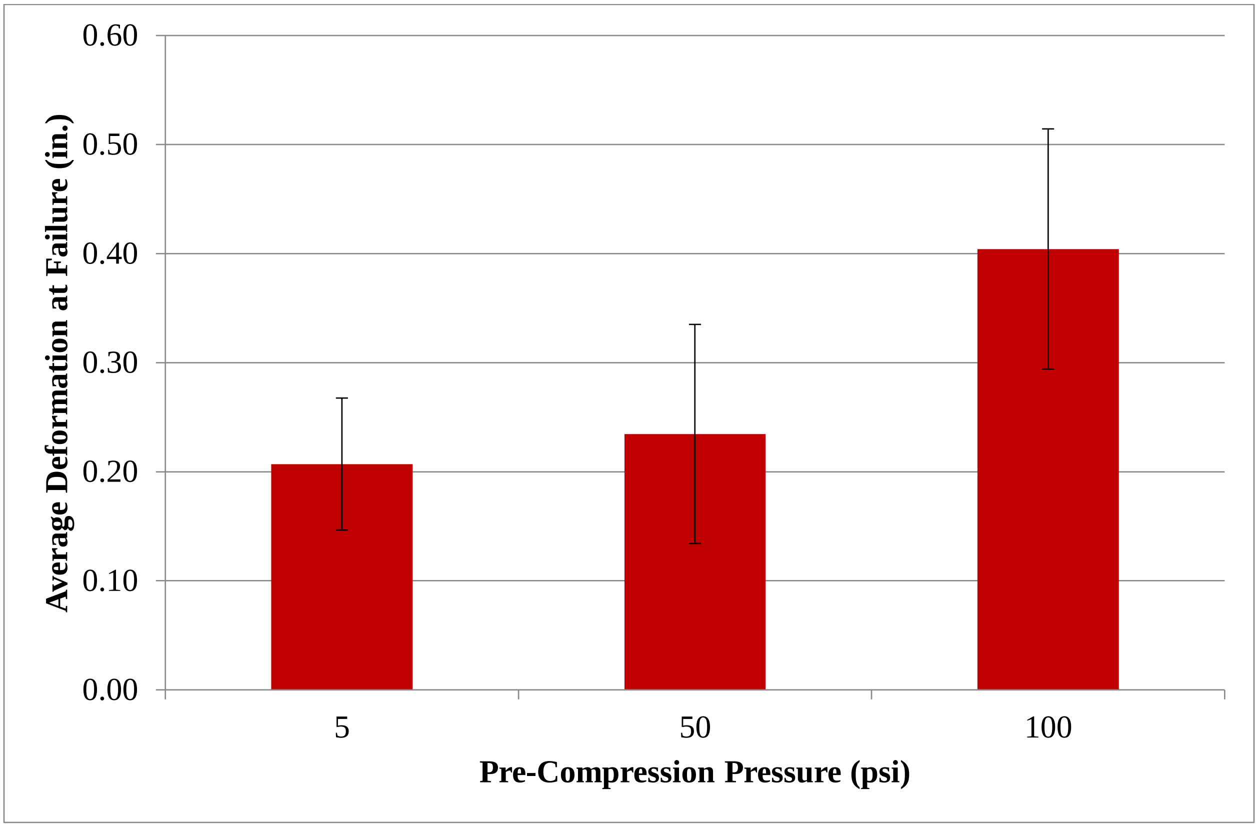
Figure 38. Average deformation at failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production

The deformation at failure of the SBCA connections decreased as pre-compression pressure increased. The opposite trend was true for the EPI connections. Samples pre-compressed under 100 psi were significantly different than both samples pre-compressed under 5 psi and 50 psi, while those pre-compressed under 5 psi and 50 psi were not significantly different from each other (**Figure 39** and **Table 15**).

The average energy until failure for samples made with the SBCA decreased as the pre-compression pressure increased (**Figure 40)** and the pressure and the energy at maximum load are inversely related. This reflects the decrease in average deformation and decrease in average tensile strength that the samples exhibited with increasing pre-compression pressure. There is no correlation between pressure and energy for the EPI connections (**Figure 41** and **Table 16**).

There was a decrease in average amount of wood failure as pre-compression pressure increased (**Figure 42**). For samples made with the SBCA wood failure decreased and there was significant variation (**Table 17**). There was a significant difference between samples pre-compressed at 5 psi to those pre-compressed under 100 psi (**Table 17**). This could be because at higher pressures more adhesive was squeezed out.

Connections made with the EPI adhesive had more wood failure at all pre-compression pressures tested than the SBCA connections. Wood failure of the EPI connections increased as pre-compression increased. Samples made with the two component EPI experienced an increase in average amount of wood failure as pre-compression pressure increased (**Figure 43** and **Table 17**). The higher amount of wood failure results in a better bond between the surfaces of the two components. All statistical analysis tests can be found in Appendix C and images of wood failure can be seen in Appendix H.



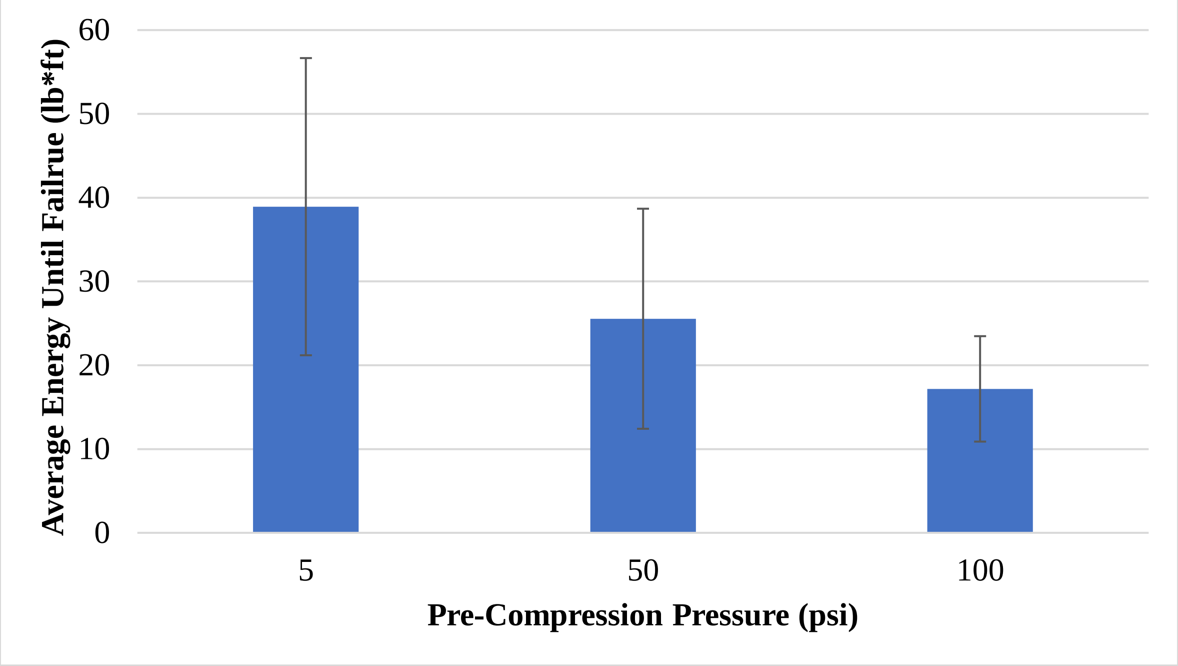
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 39. Average deformation at failure for stringerboard to deckboard connection an emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

Table 16. Summary table for average energy at failure for stringboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production

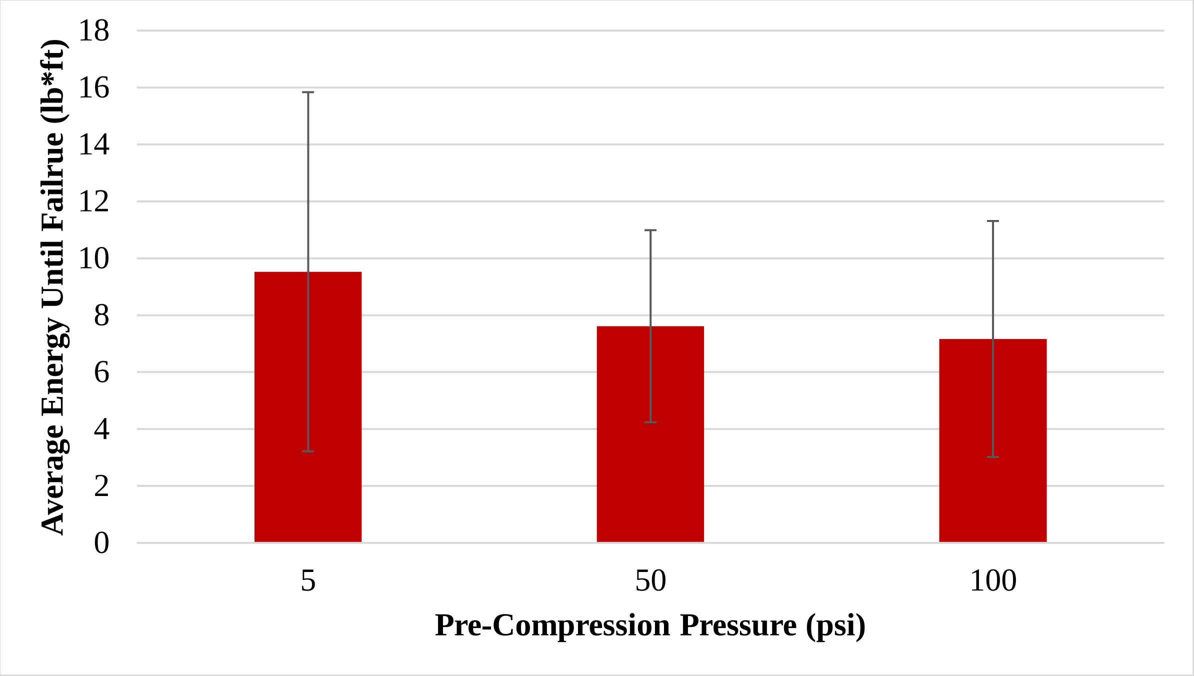
Pre-Compression Pressure (psi)	**Average Energy until Failure (ft-lb)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon**	**Mean**	**COV**	**Wilcoxon**
5	39	46%	A	10	66%	a
50	26	51%	B	8	44%	a
100	17	37%	C	7	58%	a

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 40. Average energy at failure for stringboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production



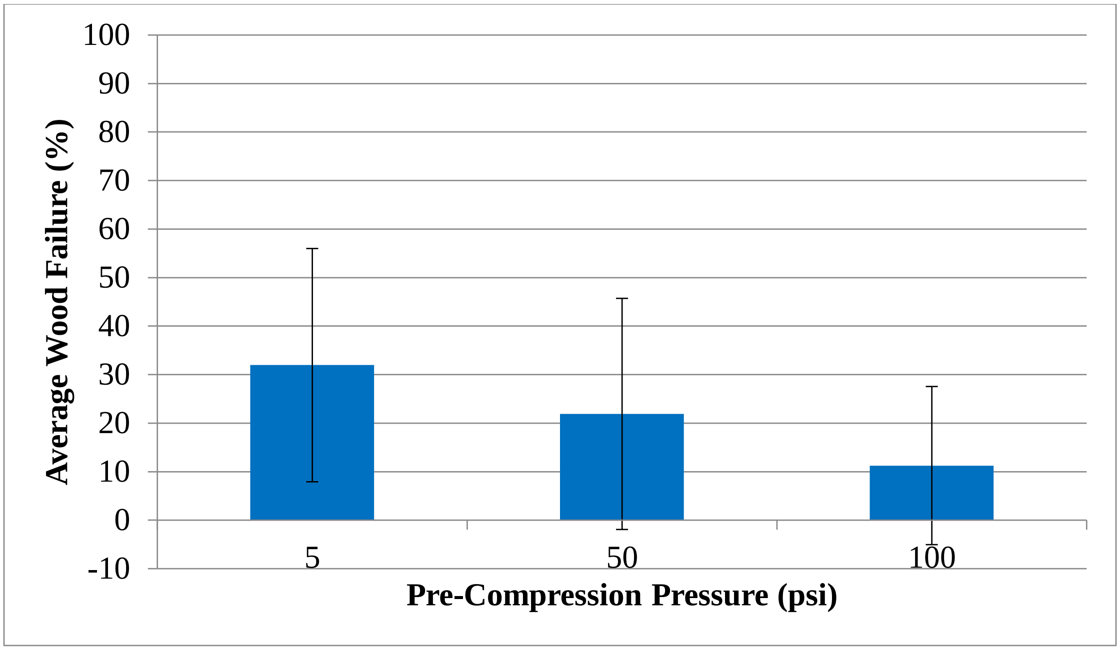
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 41. Average energy at failure for stringboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

Table 17. Summary table for average amount of wood failure for stringboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production

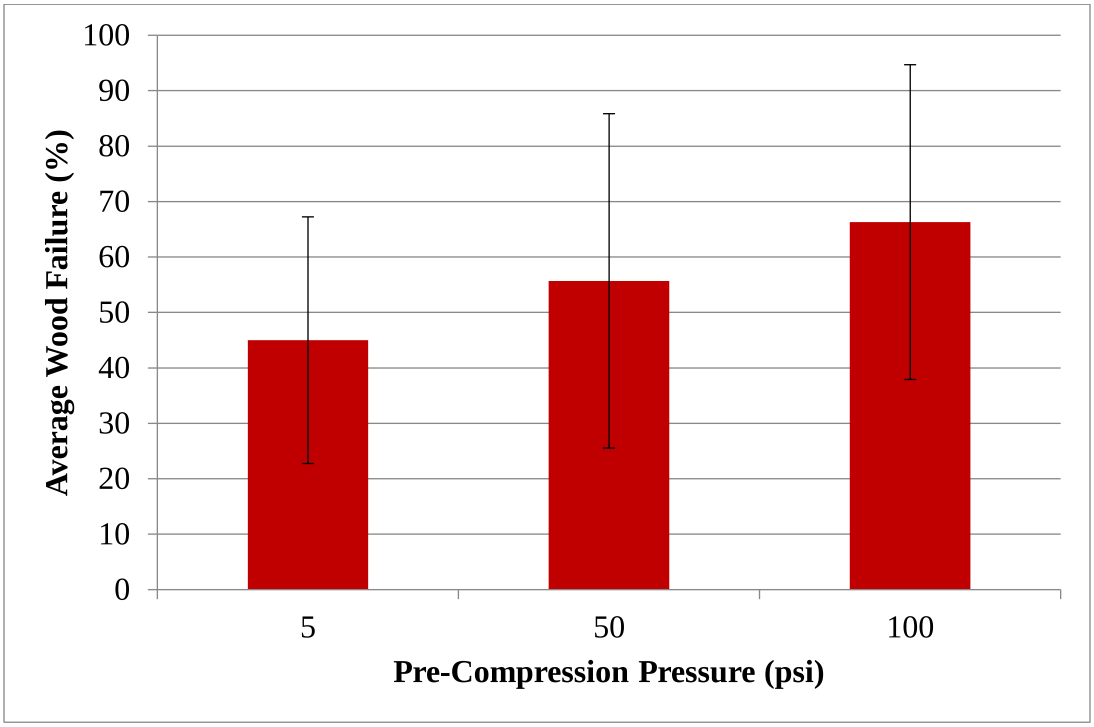
Pre-Compression Pressure (psi)	**Average Amount of Wood Failure (%)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Tukey's HSD***	**Mean**	**COV**	**Tukey's HSD***
5	32	75%	A	45	49%	a
50	22	109%	AB	56	54%	ab
100	11	145%	B	66	43%	b

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 42. Average wood failure for stringerboard to deckboard connection using a solvent based construction adhesive tested in tension parallel to the grain 7+ days after production



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 43. Average wood failure for stringerboard to deckboard connection using an emulsion polymer isocyanate (EPI) tested in tension parallel to the grain 7+ days after production

2.7.2.3 Effect of pre-compression pressure on the shear strength of the connection

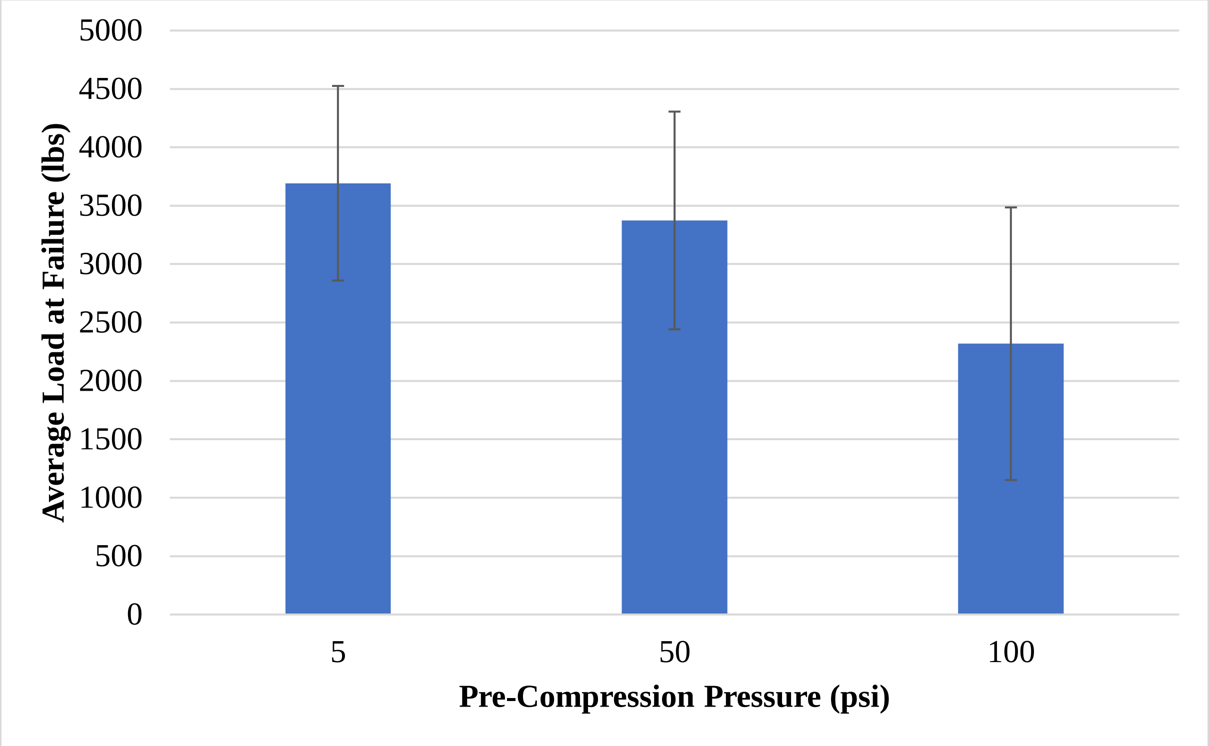
To test the shear strength of a pallet connection made with adhesive, the leading deckboard was bonded to the stringerboard, which was bonded to the block. Per the ISO 12777-3 standard, the block was held, the stringerboard was not supported, and force was applied to the deckboard. While the standard states that both directions can be tested, due to limited materials, only one direction was able to be tested. Force was applied on the deckboard perpendicular to the grain, simulating the direction in which a forklift would commonly impact that connection.

Samples made with the SBCA and tested in shear only had failure between the deckboard and the stringerboard; the stringerboard to block connection stayed intact. The samples failed at high loads at all pre-compression pressures tested with a decrease in shear strength as pre-compression pressure was increased. Samples pre-compressed under 100psi had significantly lower average shear strength than samples pre-compressed under 5psi and 50psi (**Table 18** and **Figure 44**). This same effect was seen in other conditions tested for all samples made with the SBCA due to the thinner bondlines and larger amount of squeeze-out at higher pressures.

Table 18. Summary table for average shear strength for deckboard to stringerboard to block connection using a solvent based construction tested 7+ days after production

Pre-Compression Pressure (psi)	**Average Shear Strength (lbs.)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Tukey's HSD***	**Mean**	**COV**	**Wilcoxon***
5	3693	23%	A	3783	19%	a
50	3374	28%	A	3231	35%	b
100	2318	50%	B	3516	30%	ab

*Note: Levels not connected by the same letter are significantly different



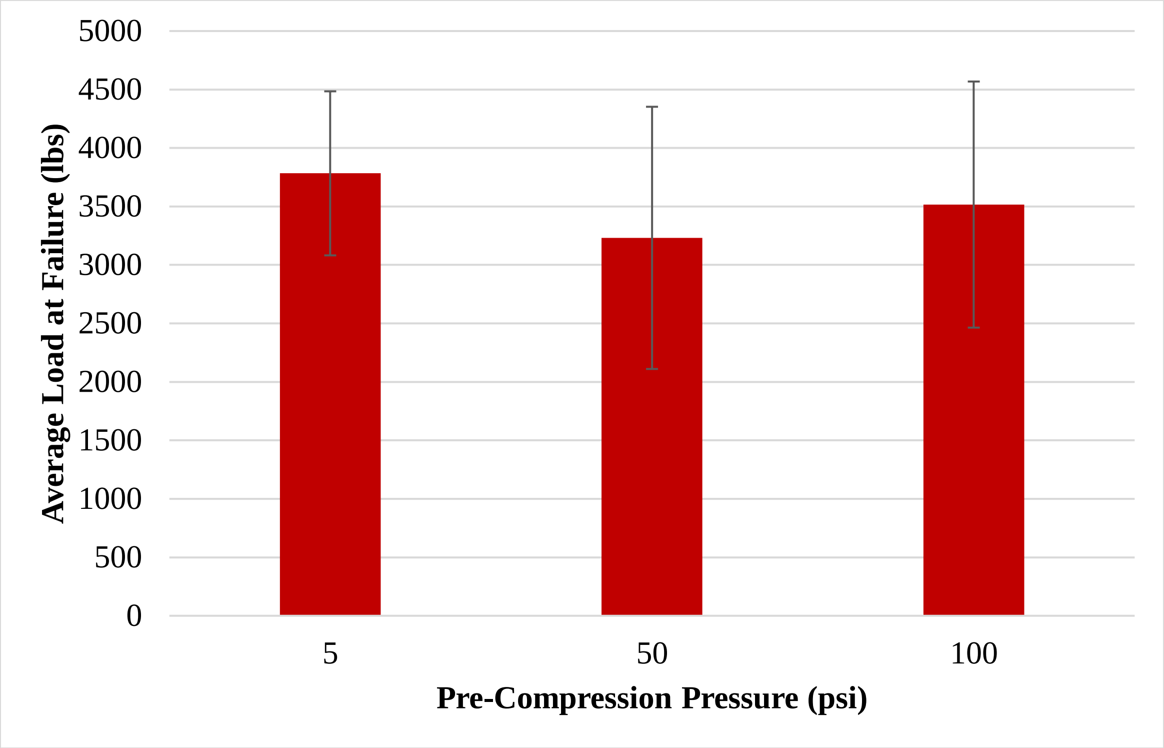
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 44. Average tensile strength for deckboard to stringerboard to block connection using a solvent based construction adhesive tested in shear 7+ days after production

Similarly to the samples that were made with the SBCA, the ones made with the two-part EPI only had failure between the deckboard and the stringerboard; the stringerboard to block connection stayed intact. They also all experienced high average shear strength at all pre-compression pressures. The average shear strength did not show any clear trend as the pre-compression pressure increased. There was a significant difference between samples pre-compressed under 5 psi to those pre-compressed under 50 psi but samples pre-compressed under 100 psi were not significantly different to either group (**Table 18** and **Figure 45**). The average shear strength for samples pre-compressed under 50 psi was lower than both other groups due to an outlier of one sample group that failed at a maximum of 291 lbs. Without the outlier, there is no significant difference between any of the groups. The pre-compression pressure did not have an effect on the shear strength of samples made with the two-part EPI. This could be attributed to the thin bondlines and low viscosity of the adhesive.

Since no samples failed at the connection between the stringerboard and the deckboard, a few samples of each adhesive were re-tested by pushing on the stringerboard in a parallel to the grain direction. All samples tested by this method were unable to be sheared, and all had compression failure in the wood of the stringerboard. The loads recorded for these tests were inaccurate; we are unable to provide exact data due to failure of the test setup equipment during the test; however, we do know that the loads exceeded 13,000 lbs.

As pressure increased, samples made with the SBCA showed a decrease in average deformation at failure (**Table 18** and **Figure 46**). Samples pre-compressed under 5psi failed at significantly higher average deformation than those pre-compressed under 50 and under 100psi.



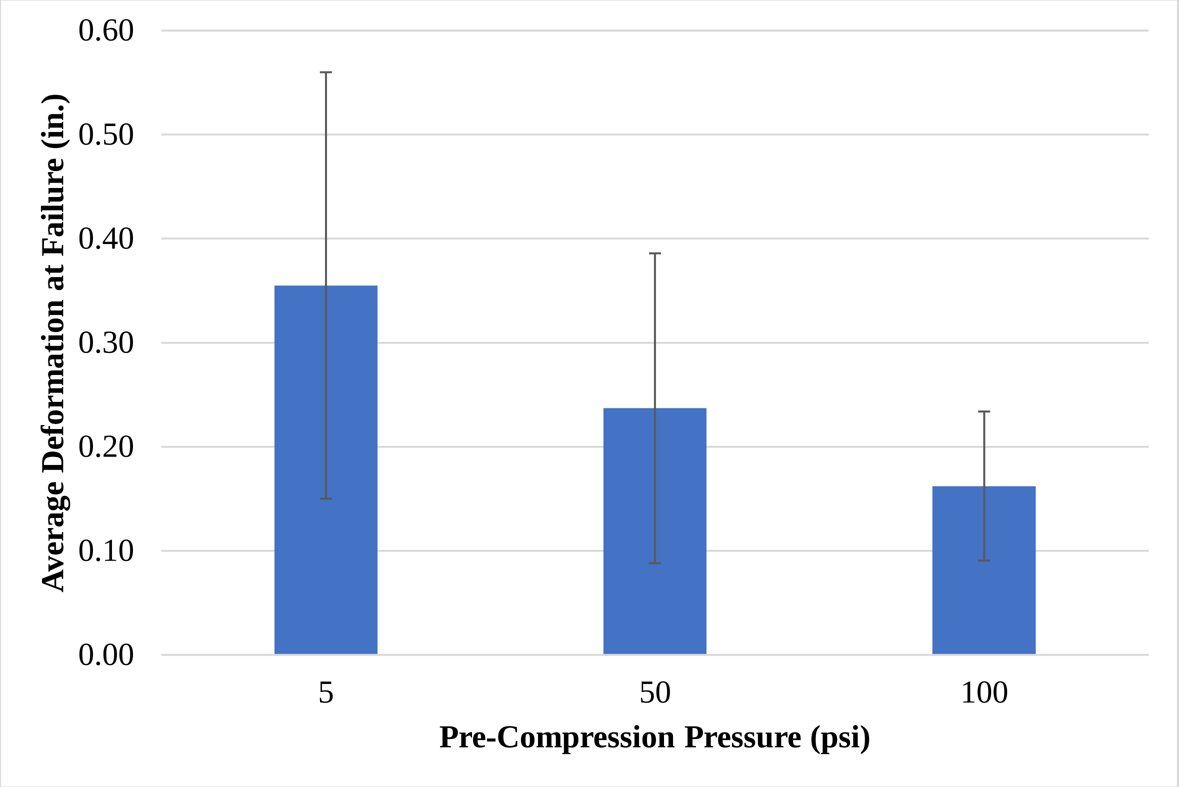
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 45. Average shear strength for deckboard to stringerboard to block connection using an emulsion polymer isocyanate (EPI) tested in shear 7+ days after production

Table 19. Summary table for average deformation at failure for deckboard to stringerboard to block connection using a solvent based construction tested in shear 7+ days after production

Pre-Compression Pressure (psi)	**Average Deformation at Failure (in.)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon ***	**Mean**	**COV**	**Wilcoxon ***
5	0.36	58%	A	0.33	71%	a
50	0.24	63%	B	0.21	44%	a
100	0.16	44%	B	0.26	44%	a

*Note: Levels not connected by the same letter are significantly different



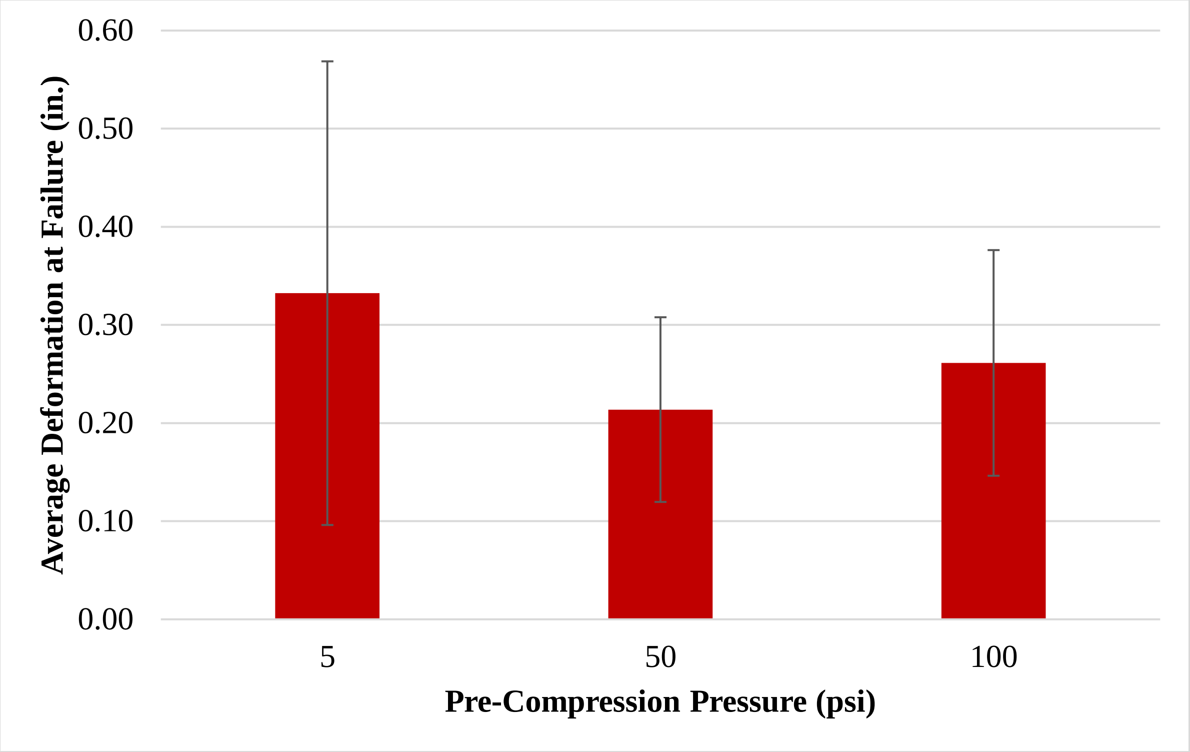
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 46. Average deformation at failure for deckboard to stringerboard to block connection using a solvent based construction adhesive tested in shear 7+ days after production

As the pre-compression pressure increased, samples made with the two-part EPI did not show a clear trend of deformation at failure (**Table 19** and **Figure 47**). Samples pre-compressed under 5psi had more variance than those pre-compressed under 50 and under 100psi but none of these groups were significantly different.

The average energy at failure for samples made with the SBCA followed the same trend of decreasing as pre-compression pressure increased as the shear strength and the deformation at failure did (**Figure 48** and **Table 20**). There was a significant difference in the average energy until failure after each pre-compression pressure increase. This decrease could be due to higher amount of squeeze-out and thinner bondlines that formed with the increasing of pre-compression pressures.

There was no clear trend in the average energy until failure for samples made with the two-part EPI as pre-compression pressure increased. Samples made with 5psi pre-compression pressure had very high variations in comparison to samples pre-compressed with 50psi and 100psi. Samples made with 5psi pre-compression pressure also had a higher average failure than samples pre-compressed under 50psi and 100psi, (**Table 20** and **Figure 49**) reflecting both the average load at failure and the average deformation at failure; however, there was no significant differences with change in pre-compression pressures.



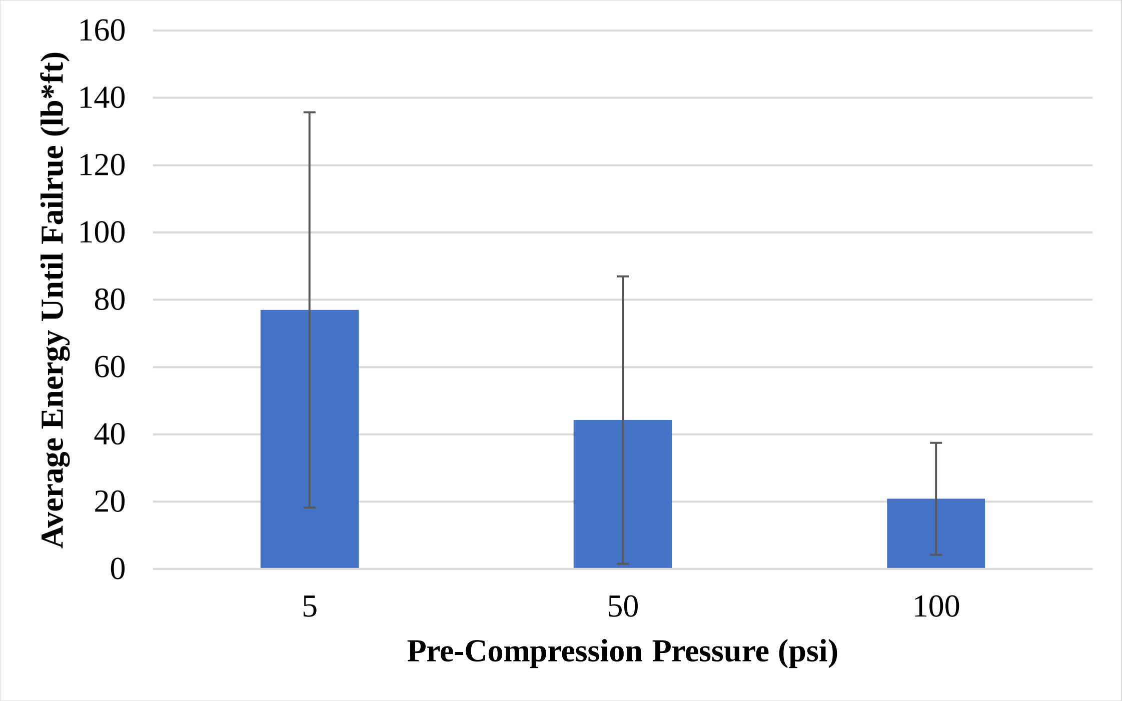
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 47. Average deformation at failure for deckboard to stringerboard to block connection using an emulsion polymer isocyanate (EPI) tested in shear 7+ days after production

Table 20. Summary table for average energy until failure for stringboard to deckboard connection using a solvent based construction adhesive and an emulsion polymer isocyanate tested in shear 7+ days after production

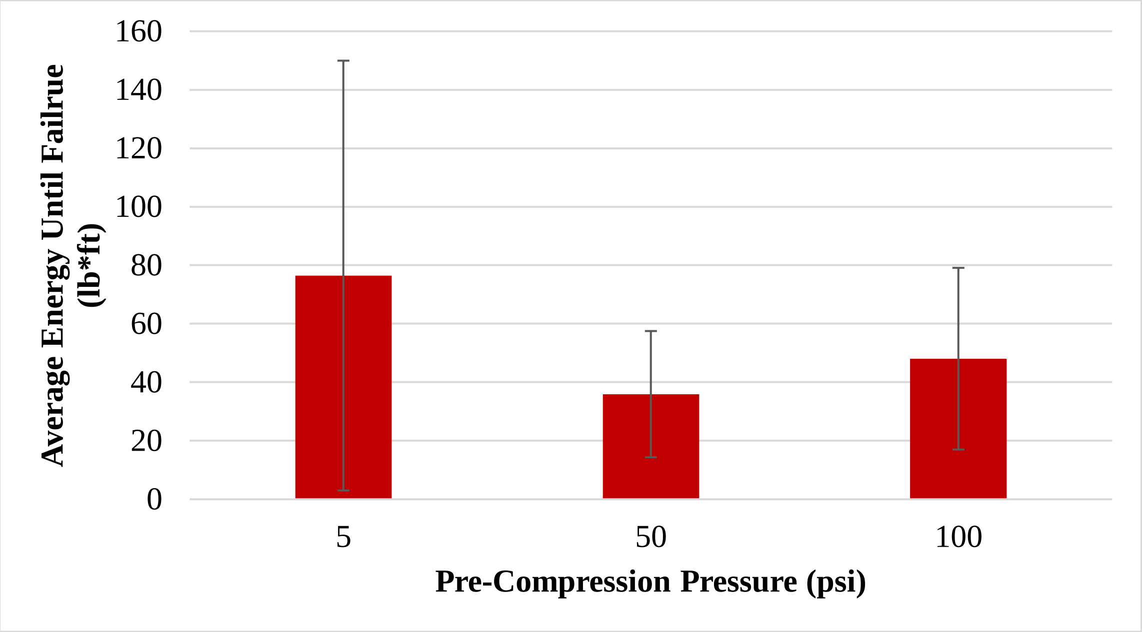
Pre-Compression Pressure (psi)	**Average Amount of Energy Until Failure (ft-lb)**					
	Solvent Based Construction Adhesive (SBCA)			**Emulsion Polymer Isocyanate (EPI)**		
	Mean	**COV**	**Wilcoxon***	**Mean**	**COV**	**Wilcoxon***
5	77	76%	A	76	96%	a
50	44	97%	B	36	60%	a
100	21	80%	C	48	65%	a

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 48. Average energy until failure for deckboard to stringerboard to block connection using a solvent based construction adhesive tested in shear 7+ days after production



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 49. Average energy until failure for deckboard to stringerboard to block connection using an emulsion polymer isocyanate (EPI) tested in shear 7+ days after production

For both the samples made with the SBCA and the samples made with the two-part EPI adhesive, failure was between the deckboard and the stringerboard, with the stringerboard to block connection staying intact. There were two methods of failure for shear testing: shear and compression. For connections that failed in shear, which was the expected method of failure, the deckboard completely separated from the stringerboard, but wood failure for these was variable. For the samples that did not fail in shear, there was compression failure in the deckboards perpendicular to the grain of the wood where the force was applied. The connection to the stringerboard remained mostly intact, but these were considered as high amounts of wood failure (95-100%).

Samples made with the SBCA under 5psi were the group that experienced the most compression failure, with 80% (16/20) of samples failing under compression, while both other groups made with the same adhesive had only 5% (1/20) of samples failing under compression (**Table 21** and **Figure 50**). Statistical analysis tests comparing the samples made with the Titebond Heavy Duty construction adhesive under different pre-compression pressures could not be conducted due to only one of the samples from the groups pre-compressed under 50psi and under 100psi failing under compression.

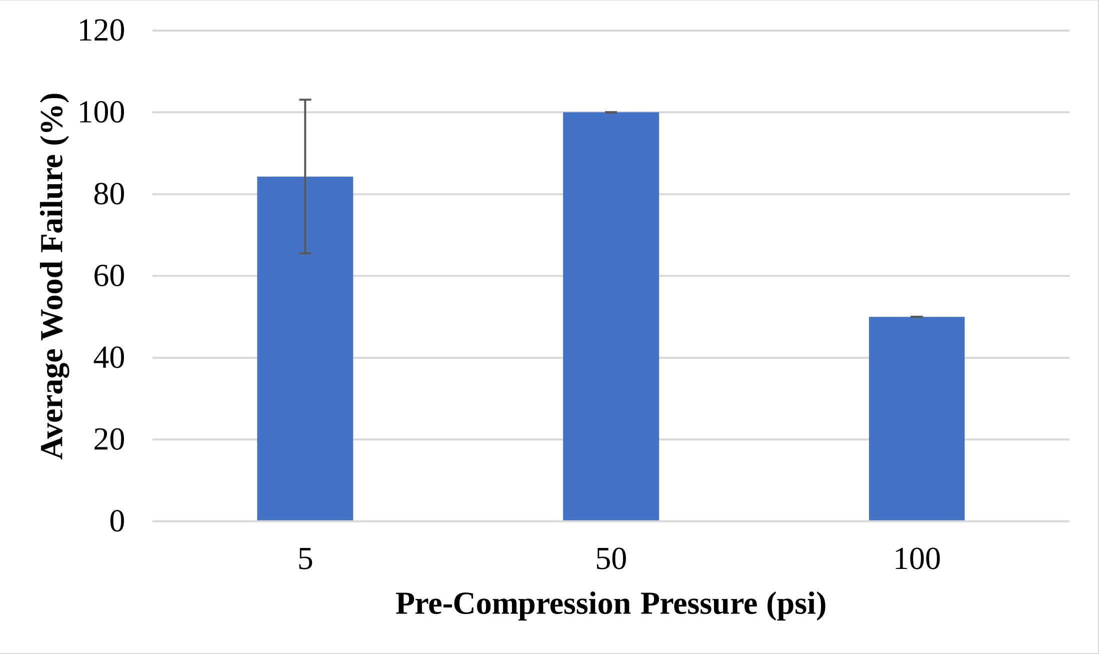
Samples made with the SBCA that did not fail in compression, but failed in shear, had low amounts of wood failure (**Table 21** and **Figure 51)**. While samples pre-compressed under 5psi had mostly compression failures, those pre-compressed under 50psi and 100psi had mostly shear failures. However, all samples failing under shear had low amounts of wood failure. There was no significant difference between samples pre-compressed under 5, 50, and 100psi, with all groups of samples having very little wood failure.

Fewer samples failed under compression out of those that had been made with the two-part EPI than of the samples made with the SBCA, but all had high amounts of wood failure (**Table 22** and **Figure 52)**. For samples made with the two-part EPI, each group had 2-3 samples that failed under compression, and there were no significant differences between the groups. However, caution should be taken when comparing these groups due to the overall low number of samples.

Table 21. Summary table for average wood failure for stringboard to deckboard connection using a solvent based construction adhesive (SBCA) tested in shear 7+ days after production failed in compression

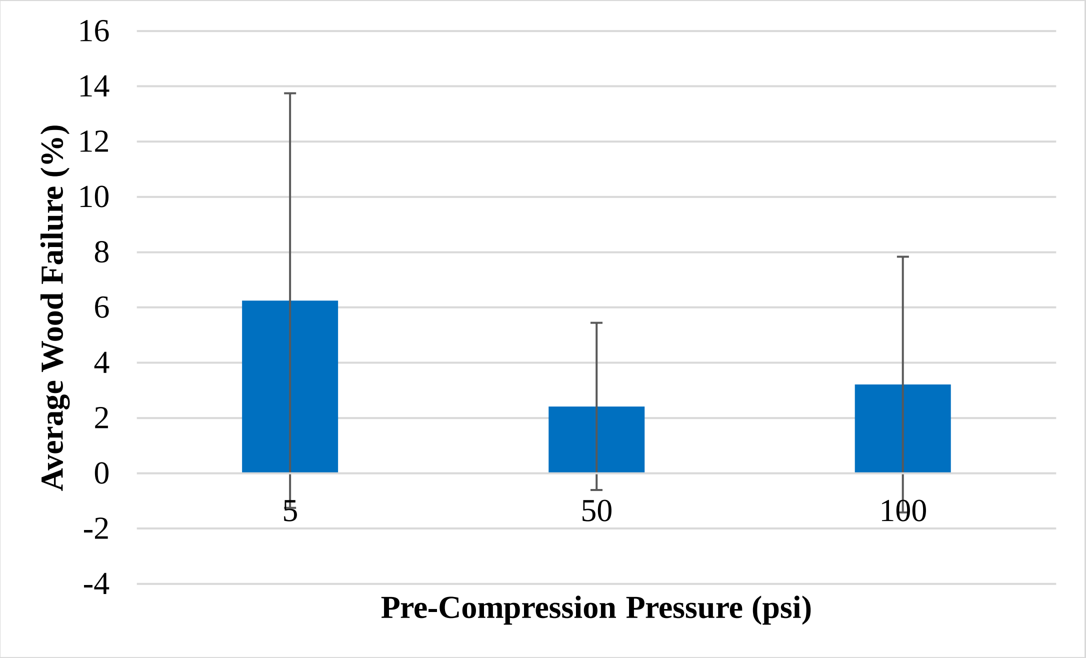
Compression Pressure (psi)	**Average Amount of Wood Failure (%) for the Solvent Based Construction Adhesive (SBCA)**					
	Compression			**Shear**		
	Mean	**COV**	**Statistics N/A**	**Mean**	**COV**	**Wilcoxon***
5	84	22%	- - -	6	120%	A
50	100	- - -	- - -	2	125%	A
100	50	- - -	- - -	3	144%	A

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 50. Average wood failure for deckboard to stringerboard to block connection using a solvent based construction adhesive (SBCA) tested in shear 7+ days after production which failed by compression failure method



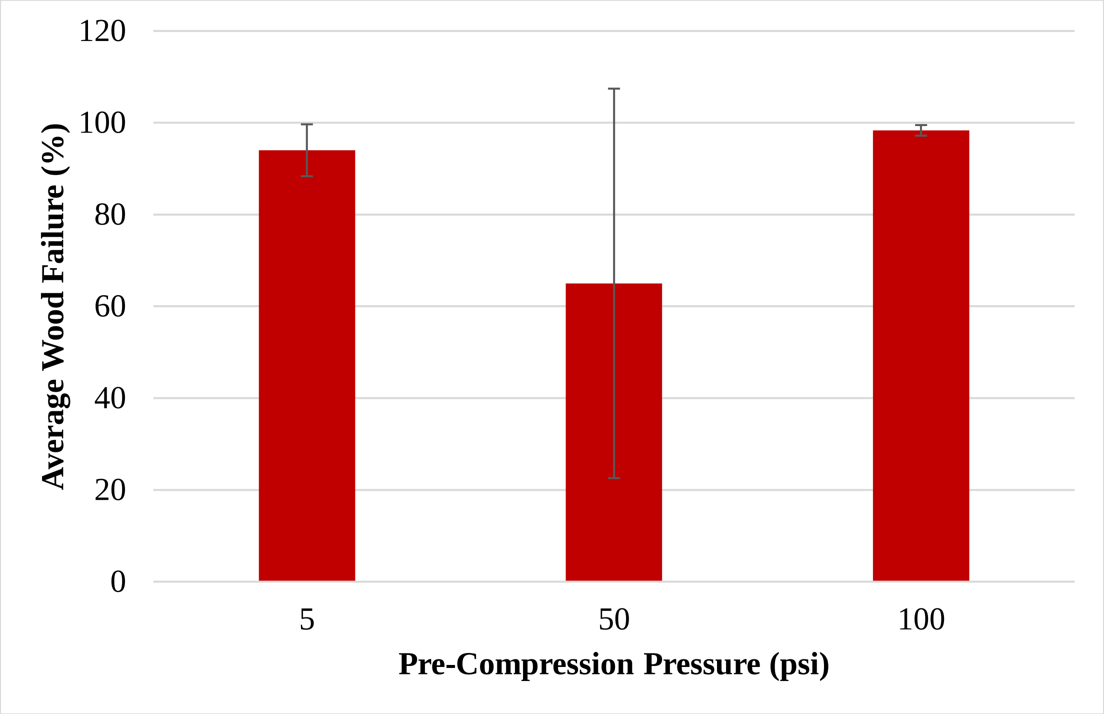
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 51. Average wood failure for deckboard to stringerboard to block connection using a solvent based construction adhesive (SBCA) tested in shear 7+ days after production with shear failure method

Table 22. Summary table for average wood failure for stringboard to deckboard connection using an emulsion polymer isocyanate adhesive (EPI) tested in shear 7+ days after production failed in compression

Compression Pressure (psi)	Average Amount of Wood Failure (%) for the Emulsion Polymer Isocyanate (EPI) adhesive					
	Compression			Shear		
	Mean	COV	Wilcoxon*	Mean	COV	Tukey's HSD*
5	94	6%	A	50	49%	a
50	65	65%	A	57	33%	ab
100	98	1%	A	68	30%	b

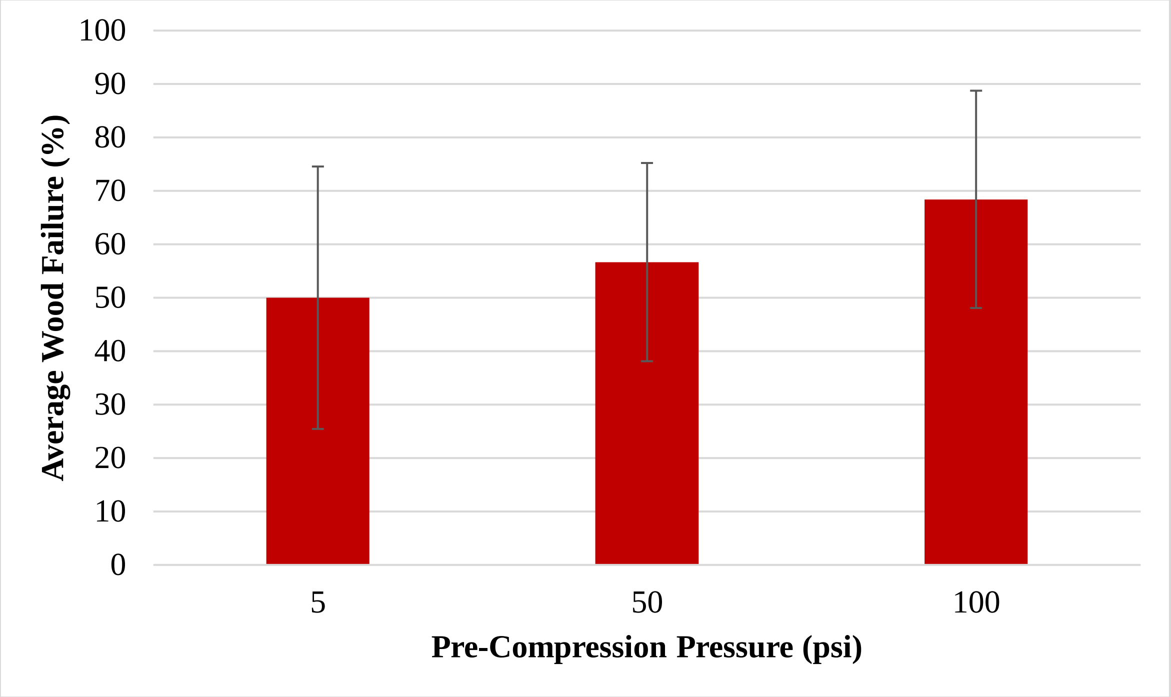
*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 52. Average wood failure for deckboard to stringerboard to block connection using an emulsion polymer isocyanate (EPI) tested in shear 7+ days after production with compression failure method

Most samples made with the EPI failed in shear rather than compression and had higher amounts of wood failure than samples made with the SBCA. As the pre-compression pressure increased, the average amount of wood failure increased for samples made with the EPI (**Table 22** and **Figure 53)**. There was a significant difference between samples pre-compressed under 5psi to those pre-compressed under 100psi. All statistical analysis tests can be found in Appendix D and images of wood failure can be seen in Appendix G.



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 53. Average wood failure for deckboard to stringerboard to block connection using an emulsion polymer isocyanate (EPI) tested in shear 7+ days after production with shear failure method

2.7.3 Effect of connection method on the strength of the connection

2.7.3.1 Effect of connection method on the tensile strength perpendicular to the grain of the connection

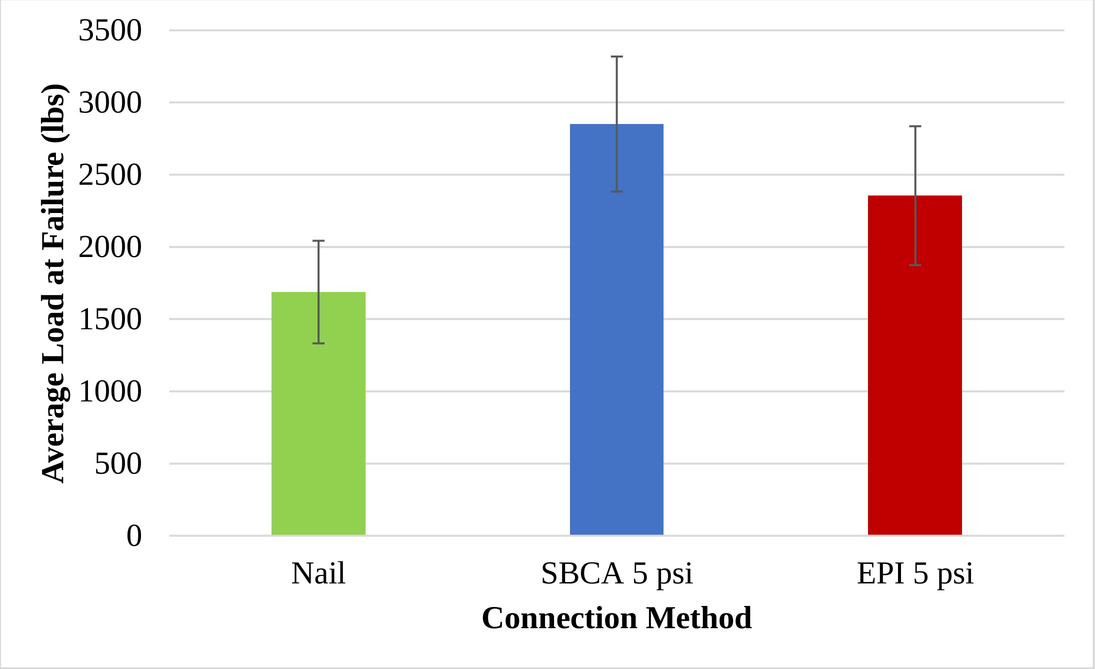
One of the objectives of this study was to compare the capabilities of adhesives to nails. A commonly used nail for block class pool pallets and two adhesives were chosen. Comparison tests were conducted. Only samples pre-compressed under 5 psi were used to compare the connection methods; in a pallet manufacturing setting lower pre-compression pressures would be ideal. The 5psi pre-compression pressure was used was because previous tests revealed that the connection made with the SBCA can handle a higher load if pre-compressed with a lower pre-compression pressure, and the connection made with the two-part EPI was not affected by changes in pre-compression pressure. Samples made with nails were made with all three pallet components (deckboard, stringerboard, and block) following the standard ISO 12777-3 (ISO, 2002). Samples made with adhesives tested the connection between the deckboard and the stringerboard (perpendicular to the grain) and the stringerboard to the block (parallel to the grain) separately for tensile strength.

Samples made with the SBCA and the two-part EPI both failed at significantly higher average loads than samples made with nails (**Table 23** and **Figure 54**) when bonded perpendicular to the grain. The higher strength in these connections could be due to the difference in the coverage area of the connection method. While nails only attach a small area, adhesives are able to cover the whole area. Nails also cause high stress points in the wood which can cause splitting, and this could be another reason why the samples made with nails have a lower average load at failure than samples made with either adhesive.

Table 23. Summary table for average load at failure for samples tested in tension perpendicular to the grain using different connection methods

Connection Method	Average Load at Failure (lbs.)	COV	Tukey's HSD
Nail	1687	21%	C
Solvent Based Construction Adhesive (SBCA) 5 psi	2851	16%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	2355	20%	B

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

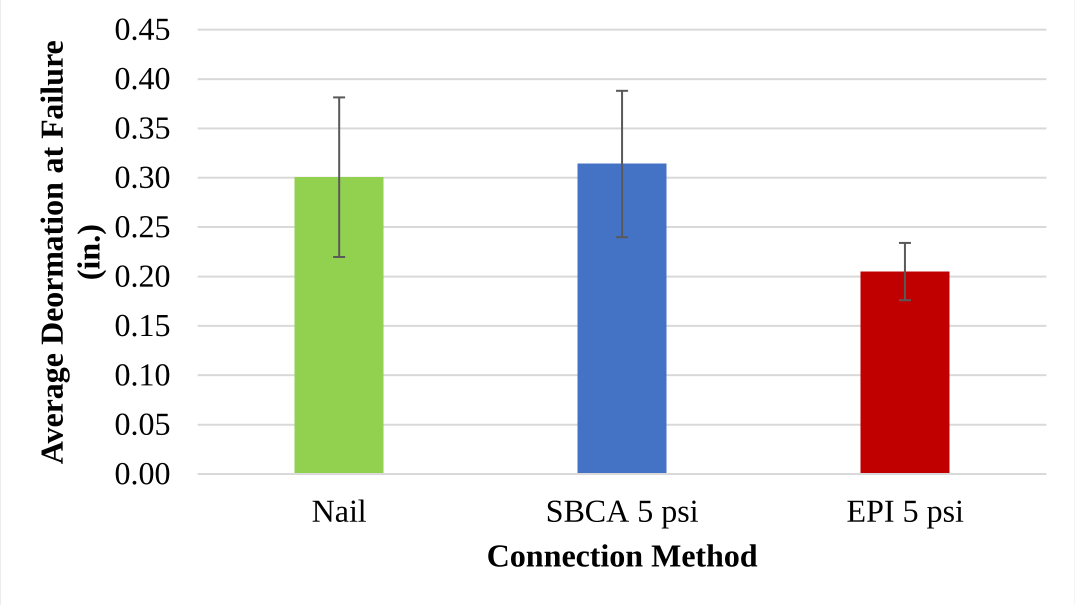
Figure 54. Average load at failure for samples tested in tension perpendicular to the grain using different connection methods

Deformation was compared between all three connection methods, and (**Table 24**) samples made with the SBCA, and pre-compressed under 5psi, were similar to those made with nails, but both had significantly different deformation from samples made with the two-part EPI pre-compressed under 5psi (**Table 24** and **Figure 55)**. Finding similar deformation between the samples made with nails and those made with the SBCA is beneficial because it shows that, when under load in tension perpendicular to the grain, the connection between the stringerboard and the deckboard could potentially behave similarly whether SBCA or nails are used as the connection method.

Table 24. Summary table for average deformation at failure for tension perpendicular to the grain using different connection methods

Connection Method	Average Deformation at Failure (in.)	COV	Wilcoxon
Nail	0.30	27%	A
Solvent Based Construction Adhesive (SBCA) 5 psi	0.31	24%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	0.21	14%	B

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

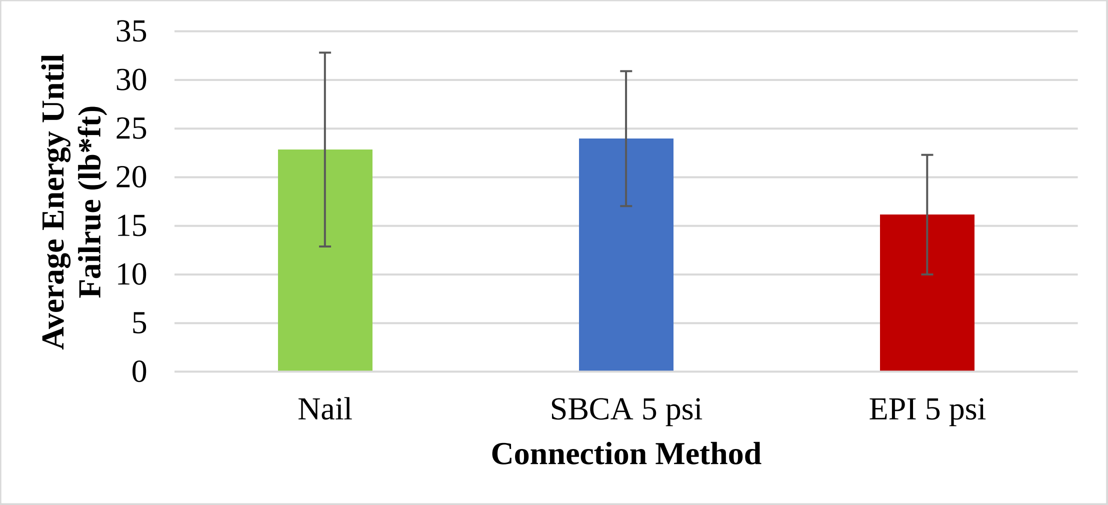
Figure 55. Average deformation at failure for samples tested in tension perpendicular to the grain using different connection methods

The average energy until failure was calculated and compared for the different connection methods. This can help give an indicator of what to expect during use. Higher energy indicates that the connection could allow for more impacts. Samples made with the SBCA failed at similar average energy to those made with nails. Those made with two-part EPI failed at significantly lower average energy than both of the other connection methods (**Table 25**). Although the average maximum load at failure for samples made with both adhesives were significantly higher than those made with nails, the differences in the average amount of deformation led to the energy until failure for the SBCA being statistically similar to nails, but the two-part EPI adhesive was significantly lower than either the samples made with nails or the samples made with the SBCA (**Figure 56**).

Table 25. Summary table for average energy at failure for tension perpendicular to the grain using different connection methods

Connection Method	Average Energy until Failure (ft-lb)	COV	Wilcoxon*
Nail	23	44%	A
Solvent Based Construction Adhesive (SBCA) 5 psi	24	29%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	16	38%	B

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 56. Average energy at failure for tension perpendicular to the grain using different connection methods

Nailed samples tested in tension failed primarily with the nails withdrawing from the block, while still attached to the deckboard and stringerboard. Nail heads pulled through the deckboard but was seen less often. All statistical analysis tests can be found in Appendix E and images of failure can be seen in Appendix H.

2.7.3.2 Effect of connection method on the tensile strength parallel to the grain of the connection

The same nailed samples were used to compare the tensile strength for samples bonded perpendicular to the grain as were used to compare the samples bonded parallel to the grain. Samples made with the SBCA that were pre-compressed under 5psi were significantly stronger than those made with the two-part EPI adhesive that were also pre-compressed under 5psi, and also stronger than those made with nails (**Figure 57** and **Table 26**). This could be due to the difference in the coverage area of the connection method.

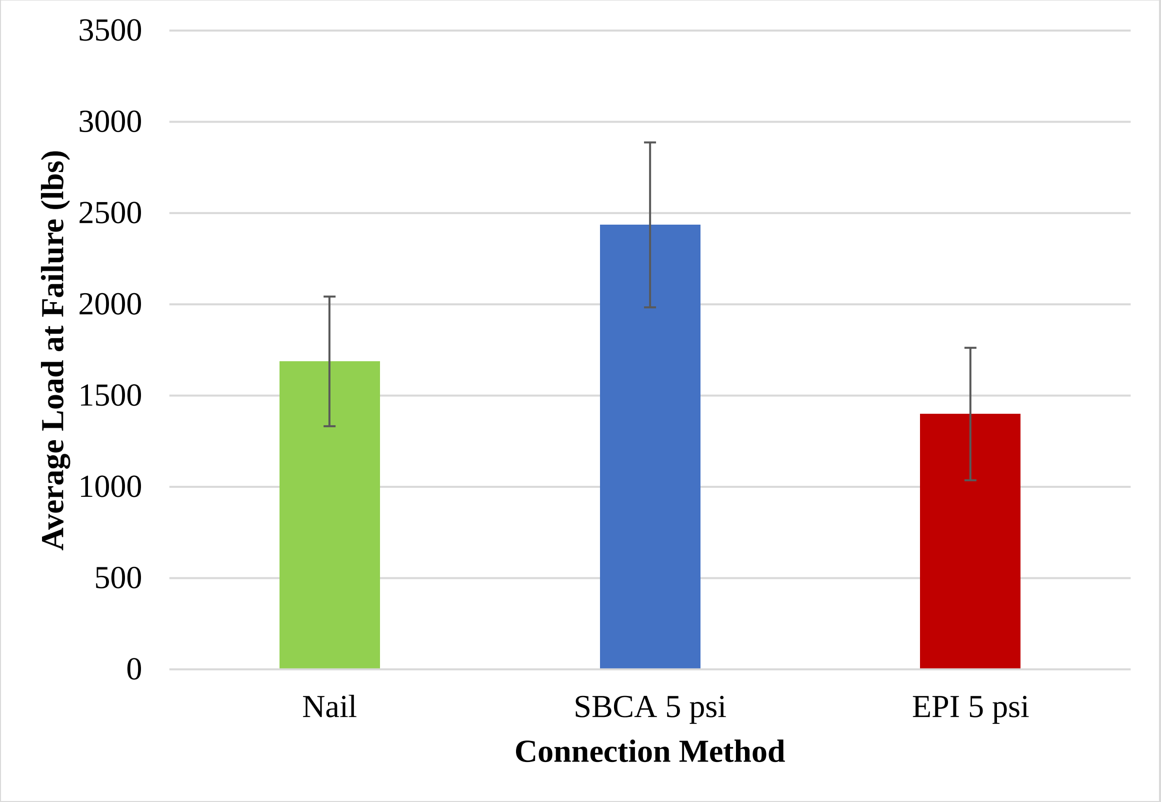
The two-part EPI adhesive was brittle, and it had a lower average deformation at failure than those made with nails. Samples made with the SBCA had a higher average deformation at failure than either of the other sample groups (**Figure 58** and **Table 27)**. This could be due to the connection withstanding higher average loads or because of the elasticity of the adhesive.

Samples made with the SBCA pre-compressed under 5psi had the highest average energy until failure, followed by the samples made with nails, and then the samples made with the two-part EPI adhesive and pre-compressed under 5psi were the lowest. This trend was seen both in the average tensile strength and the average deformation at failure of the different connection methods (**Table 28** and **Figure 59**). Similarly to the average deformation at failure, there were significant differences between all three connection methods, with samples made with the SBCA having the highest energy until failure. All statistical analysis tests can be found in Appendix F and images of failure can be seen in Appendix H.

Table 26. Summary table for average load at failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

Connection Method	Max Load Average (lbs.)	COV	Tukey's HSD
Nail	1687	21%	B
Solvent Based Construction Adhesive (SBCA) 5 psi	2435	19%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	1399	26%	B

*Note: Levels not connected by the same letter are significantly different



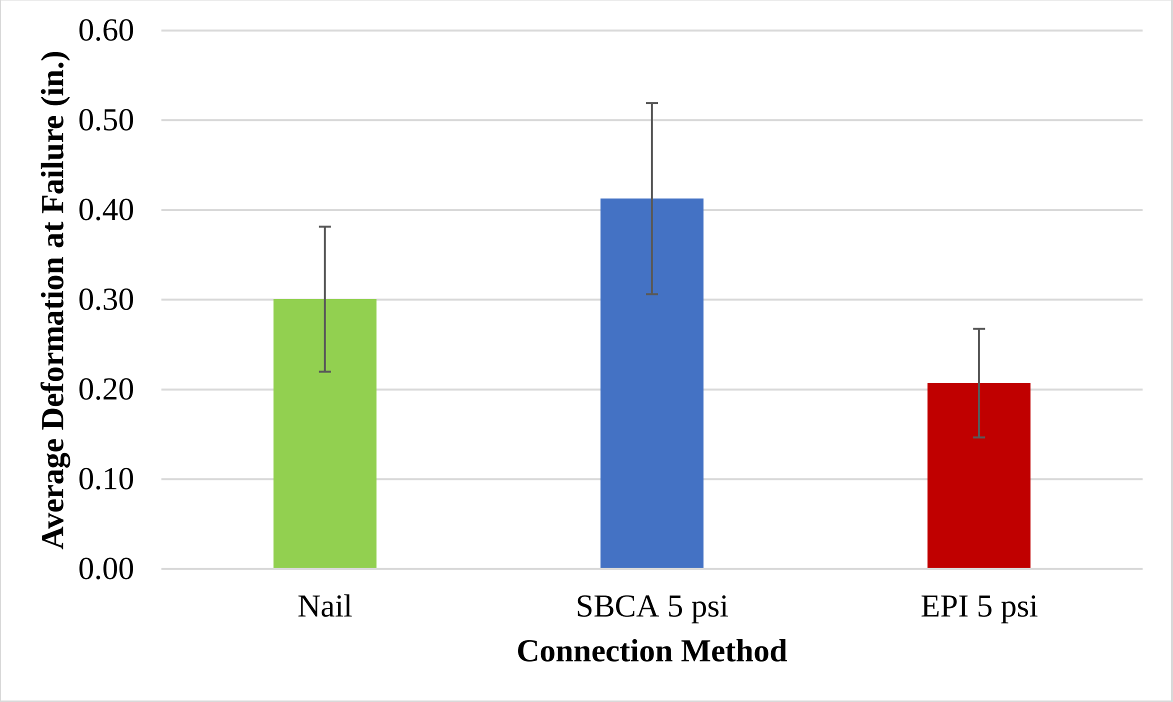
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 57. Average load at failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

Table 27. Summary table for average deformation at failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

Connection Method	**Deformation (in.)**	**COV**	**Wilcoxon**
Nail	0.30	27%	B
Solvent Based Construction Adhesive (SBCA) 5 psi	0.41	26%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	0.21	29%	C

*Note: Levels not connected by the same letter are significantly different



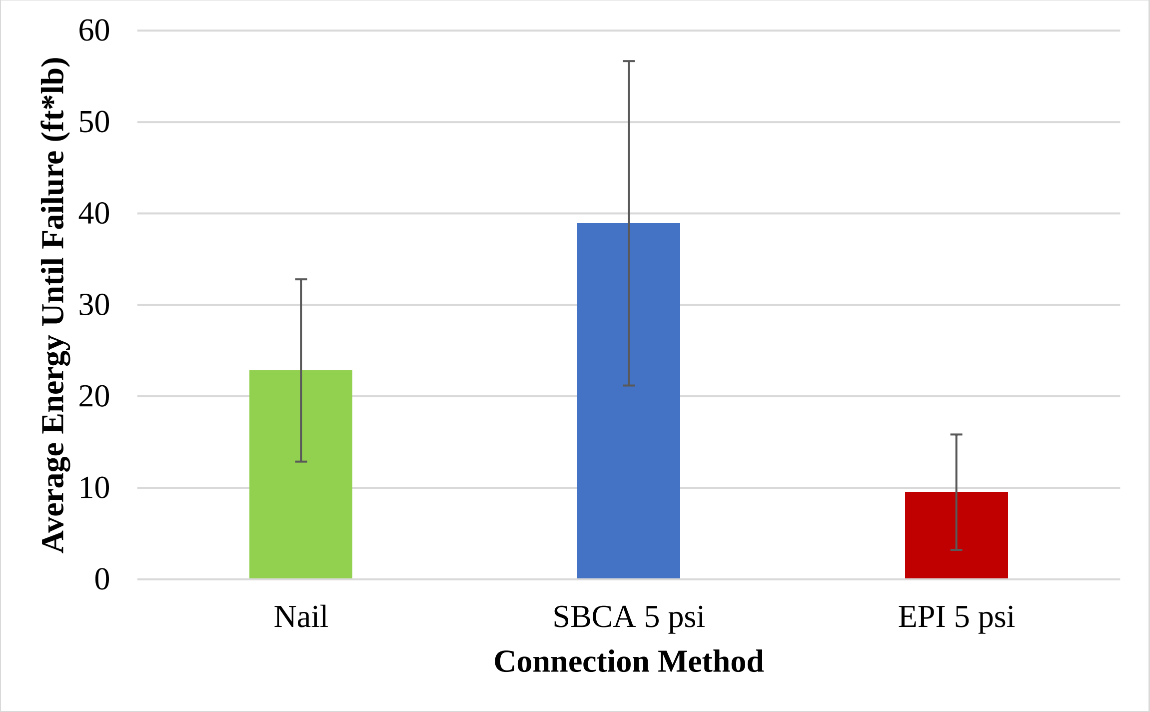
Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 58. Average deformation at failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

Table 28. Summary table for average energy until failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

Connection Method	**Energy Until Failure (ft-lb)**	**COV**	**Wilcoxon**
Nail	23	44%	B
Solvent Based Construction Adhesive (SBCA) 5 psi	39	46%	A
Emulsion Polymer Isocyanate (EPI) 5 psi	10	66%	C

*Note: Levels not connected by the same letter are significantly different



Note: Each error bar is constructed using 1 standard deviation from the mean

Figure 59. Average energy until failure for stringerboard to block connection using different connection methods tested in tension parallel to the grain

2.7.3.3 Effect of connection method on the shear strength of the connection

The connection of the lead deckboard to stringerboard to block was tested in shear following ISO standard 12777-3 (ISO, 2002). The standard states that the connection can be tested in two directions; however, due to limited materials, samples made with the adhesives were only tested in one direction. The force for those samples was applied perpendicular to the grain of the deckboard. Samples made with nails were tested with force applied both perpendicularly and parallel to the grain of the deckboard.

Samples made with both the SBCA and the two-part EPI adhesive failed, on average, at twice the load of the samples made with nails (**Figure 60** and **Table 29)**. There was no significant difference between nailed samples tested with the load applied perpendicular to the grain and the nailed samples with the load applied parallel to the grain. There was also no difference between samples made with the SBCA to the ones made with the two-part EPI adhesive. There was, however, a significant difference between the samples made with nails and the samples made with adhesives. This higher average shear strength in the samples made with the adhesives could be due to the ability of the adhesives to cover the full area of the connection. Nails, by their nature, are unable to do this. Nails also create a high stress point that can cause splitting in the wood.

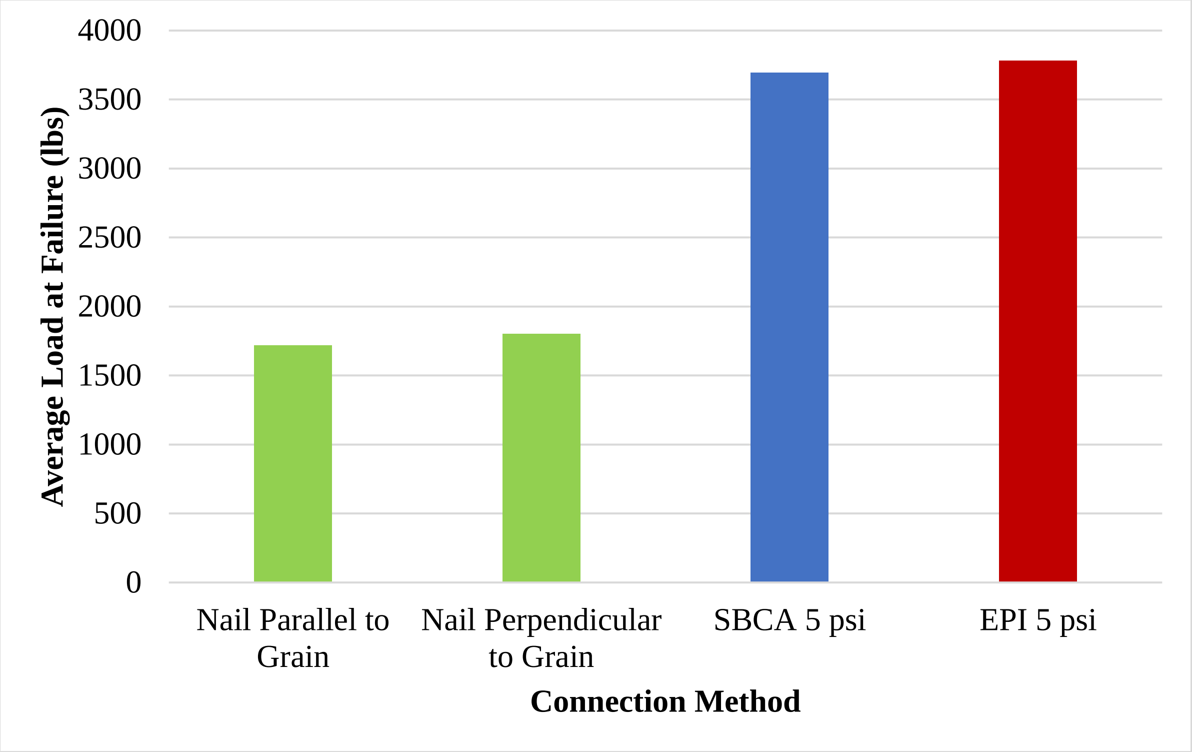


Figure 60. Average shear strength for lead deckboard pallet connection using different connection methods tested in shear

Table 29. Summary table for average shear strength for lead deckboard pallet connection using different connection methods tested in shear

Connection Method	Average Load at Failure (lbs.)	COV	Wilcoxon
Nail Loaded Parallel to Grain	1815	12%	B
Nail Loaded Perpendicular to Grain	1766	12%	B
SBCA 5 psi	3693	23%	A
EPI 5 psi	3783	19%	A

Although samples made with nails had lower average shear strength, they had much higher deformations at failure (**Figure 61** and **Table 30**). Samples made with nails tested perpendicular to the deckboard grain failed at a significantly higher average deformations than those tested parallel to the deckboard grain. All samples made with nails, and tested in both directions, had significantly higher deformation at failure than all of the samples made with adhesives. And, samples made with the SBCA had similar deformation at failure to those made with the two-part EPI adhesive.

Deformations for samples made with nails were not only between the deckboard and the stringerboard but also between the stringerboard and the block since the nails went through all three components; whereas, adhesives created a connection only on the surfaces of these components. While stiffness can allow for higher strength, it can cause limitation to the deformation of the connections prior to and up to failure. Nails have good flexibility before failure. This can be an advantage in use because nails can give an indication prior to failure by showing movement at the connection, while adhesives can be stiffer than nails and not show this movement (Frackiewicz, 1983). Deformation for samples made with adhesives is primarily experienced between the deckboard and the stringerboard, since there was no failure between the stringerboard and the block.

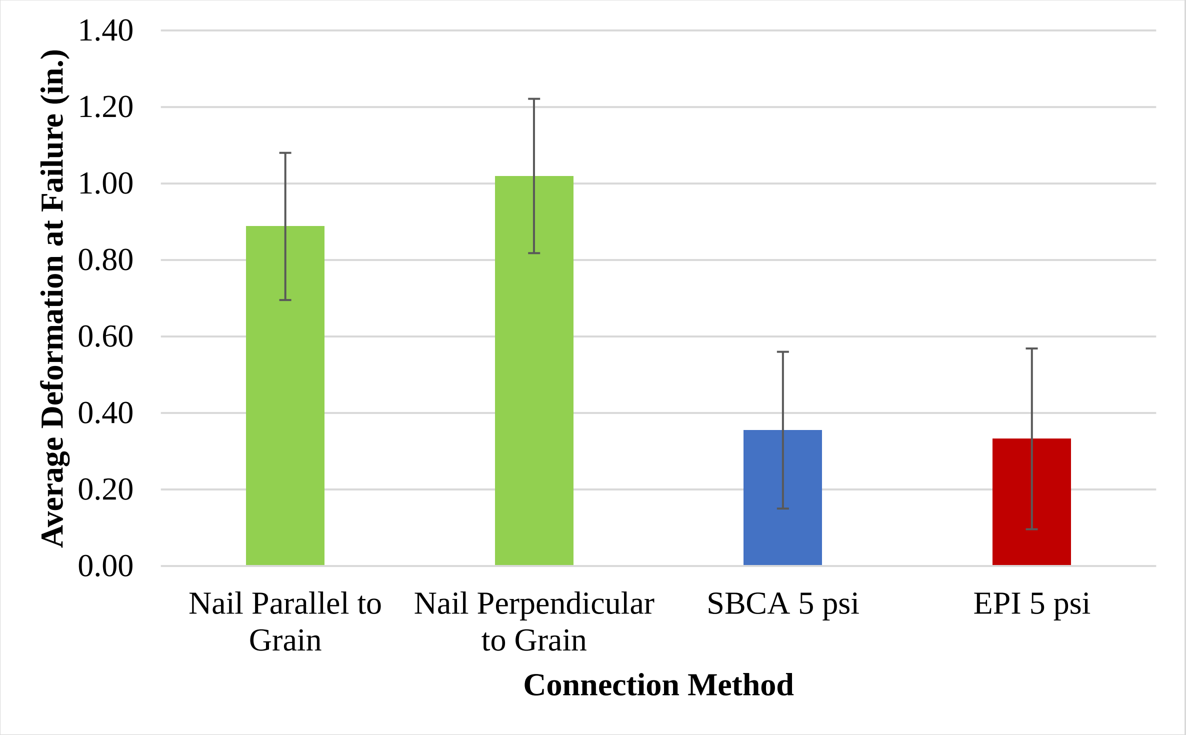


Figure 61. Average deformation at failure for lead deckboard pallet connection using different connection methods tested in shear

Table 30. Summary table for average deformation at failure for lead deckboard pallet connection using different connection methods tested in shear

Connection Method	Deformation Average (in.)	COV	Wilcoxon
Nail Loaded Parallel to Grain	0.89	22%	B
Nail Loaded Perpendicular to Grain	1.02	20%	A
SBCA 5 psi	0.36	58%	C
EPI 5 psi	0.33	71%	C

The energy was calculated from the area under the load-deformation curve. While the average shear strength of the samples made with adhesives was significantly higher than those made with nails, the opposite was seen in the average deformation at failure for the samples. This difference of which group was larger made the average energy at failure difference between groups less drastic. There were no significant differences found between the connection methods except for samples made with nails and tested perpendicular to the grain (**Table 31** and **Figure 62**). This connection group had higher energy until failure. This is how the lead deckboard most commonly experiences impact, and the amount of energy it takes to fail at this connection should be an indicator that the connection would withstand more impacts; however, the speed used during testing is drastically different than the speed that the connection would experience in regular use. Along with this, the nails cause high stress points in the wood, often leading to splitting, while adhesives do not have this issue. The amount of energy until failure is higher for nails when shear force is applied perpendicular to the grain of the deckboard, but caution should be used when determining impact capabilities.

Nailed samples tested in shear primarily failed with the nail heads pulling through the deckboard, and the deckboard and stringerboard being displaced from its original position. There was occasional splitting, however it was not commonly seen in testing. In a real-world situation splitting due to shear force would be seen more often than in testing. All statistical analysis tests can be found in Appendix G and images of failure can be seen in Appendix H.

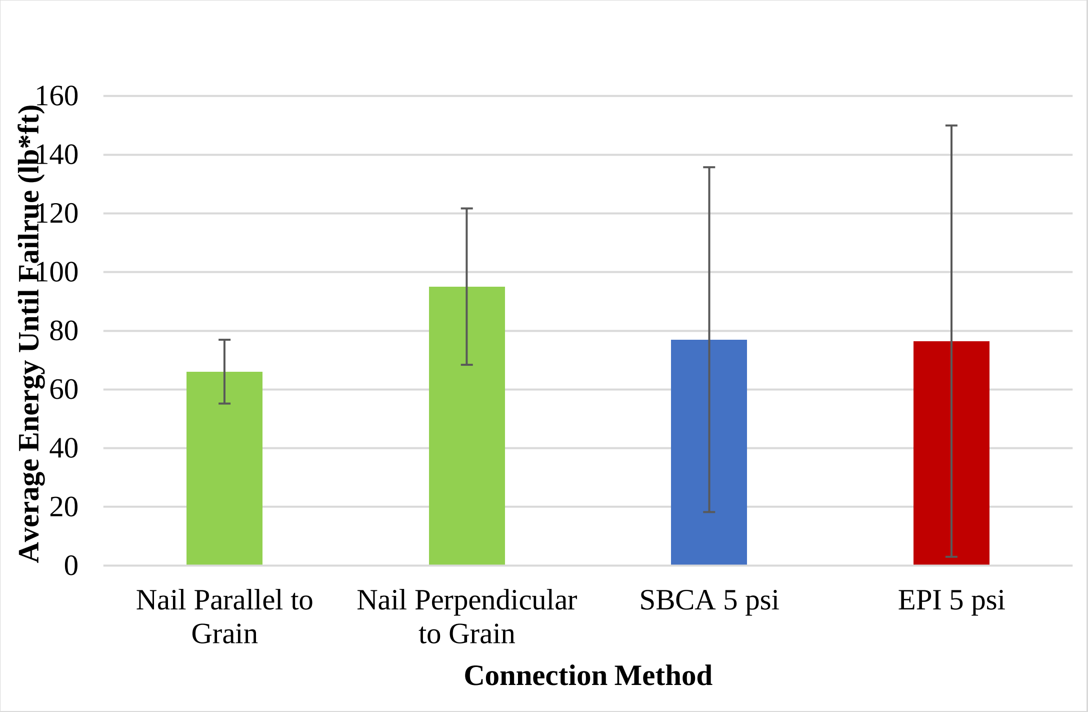


Figure 62. Average energy until failure for lead deckboard pallet connection using different connection methods tested in shear

Table 31. Summary table for average energy until failure for lead deckboard pallet connection using different connection methods tested in shear

Connection Method	**Deformation Average (in.)**	**COV**	**Wilcoxon**
Nail Loaded Parallel to Grain	66	16%	B
Nail Loaded Perpendicular to Grain	95	28%	A
SBCA 5 psi	77	76%	B
EPI 5 psi	76	96%	B

2.7.3.4 Effect of Connection Method on the Strength of the Connection

In this study, tension tests were conducted separately because they are separate connections. Samples bonded perpendicular to the grain were not compared to samples bonded parallel to the grain. Shear tests were not conducted separately due to the interaction between all components from the nails. Values from the shear tests conducted were not compared to the tension tests conducted in either direction. **Table 32** and **Figure 63** present the data for all strength tests conducted. Samples made with the SBCA had significantly higher strength, both tensile and shear, than nailed samples. The two-part EPI adhesive had similar or better strength than nailed samples. Samples made with either adhesive and tested in tension bonded perpendicular and parallel to the grain failed at lower values than those tested in shear.

Nailed samples tested in shear had significantly higher deformation than all other connections; both in tension and in shear. Samples made with the SBCA had similar or higher deformation than nailed samples when tested in tension perpendicular and parallel. Samples made with the two-part EPI adhesive had the lowest deformation of all connection methods when tested in tension perpendicular and parallel. All deformation data can be seen **Table 33** and **Figure 64**.

Table 32. Summary table for average load at failure for lead deckboard pallet connection using different connection methods

<table>
<tr><th colspan="5">Load at Failure (lbs.)</th></tr>
<tr><th>Connection Method</th><th colspan="2">Nail</th><th>Solvent Based Construction Adhesive (SBCA) 5 psi</th><th>Emulsion Polymer Isocyanate (EPI) 5 psi</th></tr>
<tr><th>Tension Perpendicular to the Grain</th><td colspan="2">1687 (21%) C</td><td>2851 (16%) A</td><td>2355 (20%) B</td></tr>
<tr><th>Tension Parallel to the Grain</th><td colspan="2">1687 (21%) B</td><td>2435 (19%) A</td><td>1399 (26%) B</td></tr>
<tr><th rowspan="2">Shear</th><th>Loaded Perpendicular to the Grain</th><th>Loaded Parallel to the Grain</th><td rowspan="2">3693 (26%) A</td><td rowspan="2">3783 (19%) A</td></tr>
<tr><td>1766 (12%) B</td><td>1815 (12%) B</td></tr>
</table>

Note: Data is presented as average load at failure (lbs.), the numbers in parentheses are Coefficient of Variance values, and statistical analysis presented as groups connected by the same letter not being significantly different based on Tukey’s HSD tests using alpha 0.05

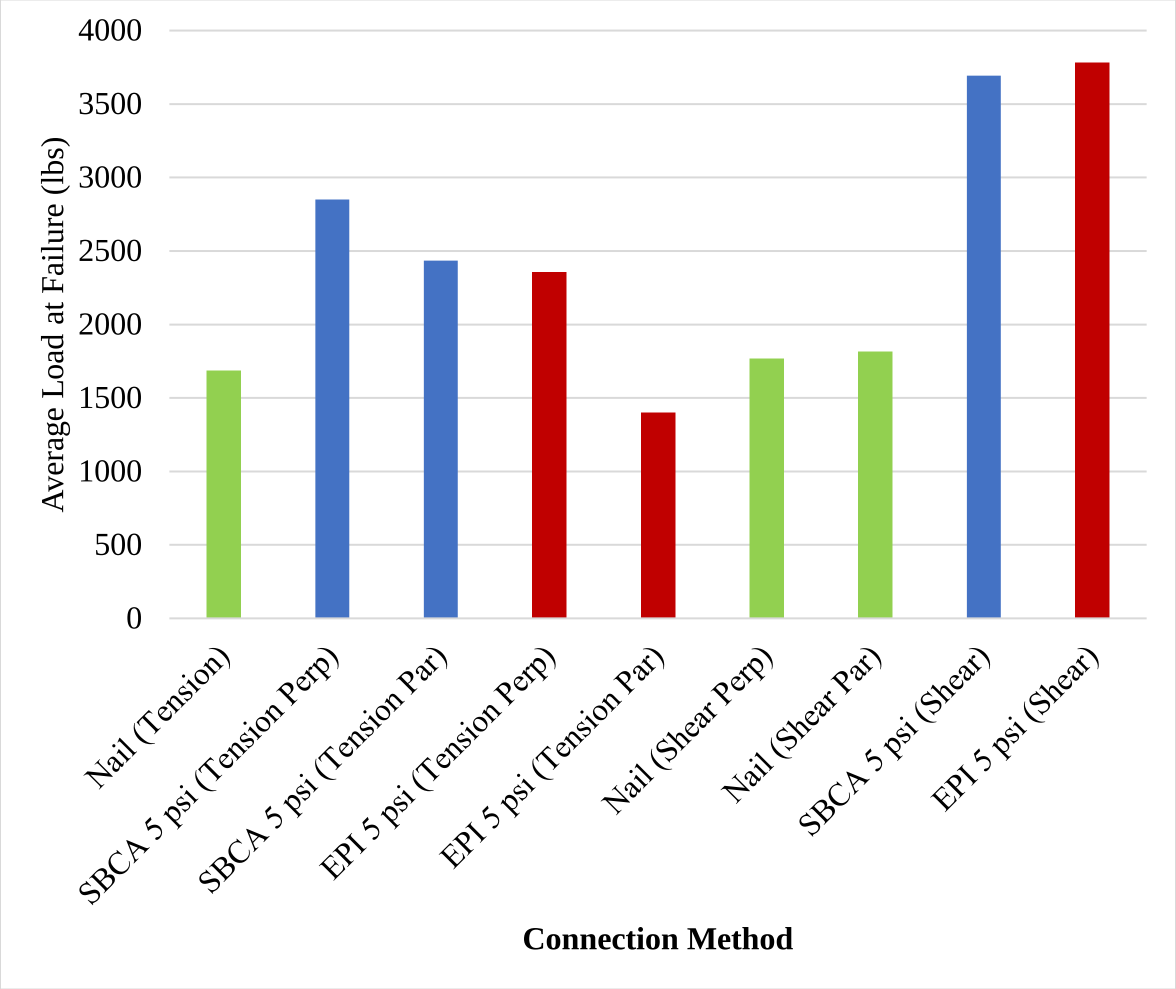


Figure 63. Average load at failure for lead deckboard pallet connection using different connection methods

Table 33. Summary table for average deflection at failure for lead deckboard pallet connection using different connection methods

Deformation at Failure (in.)				
Connection Method	**Nail**		**Solvent Based Construction Adhesive (SBCA) 5 psi**	**Emulsion Polymer Isocyanate (EPI) 5 psi**
Tension Perpendicular to the Grain	0.30 (27%) A		0.31 (24%) A	0.21 (14%) B
Tension Parallel to the Grain	0.30 (27%) B		0.41 (26%) A	0.21 (29%) B
Shear	**Loaded Perpendicular to the Grain**	**Loaded Parallel to the Grain**	0.36 (58%) C	0.33 (71%) B
	1.02 (20%) A	0.89 (22%) B		

Note: Data is presented as average load at failure (lbs.), the numbers in parentheses are Coefficient of Variance values, and statistical analysis presented as groups connected by the same letter not being significantly different based on Wilcoxon tests using alpha 0.05

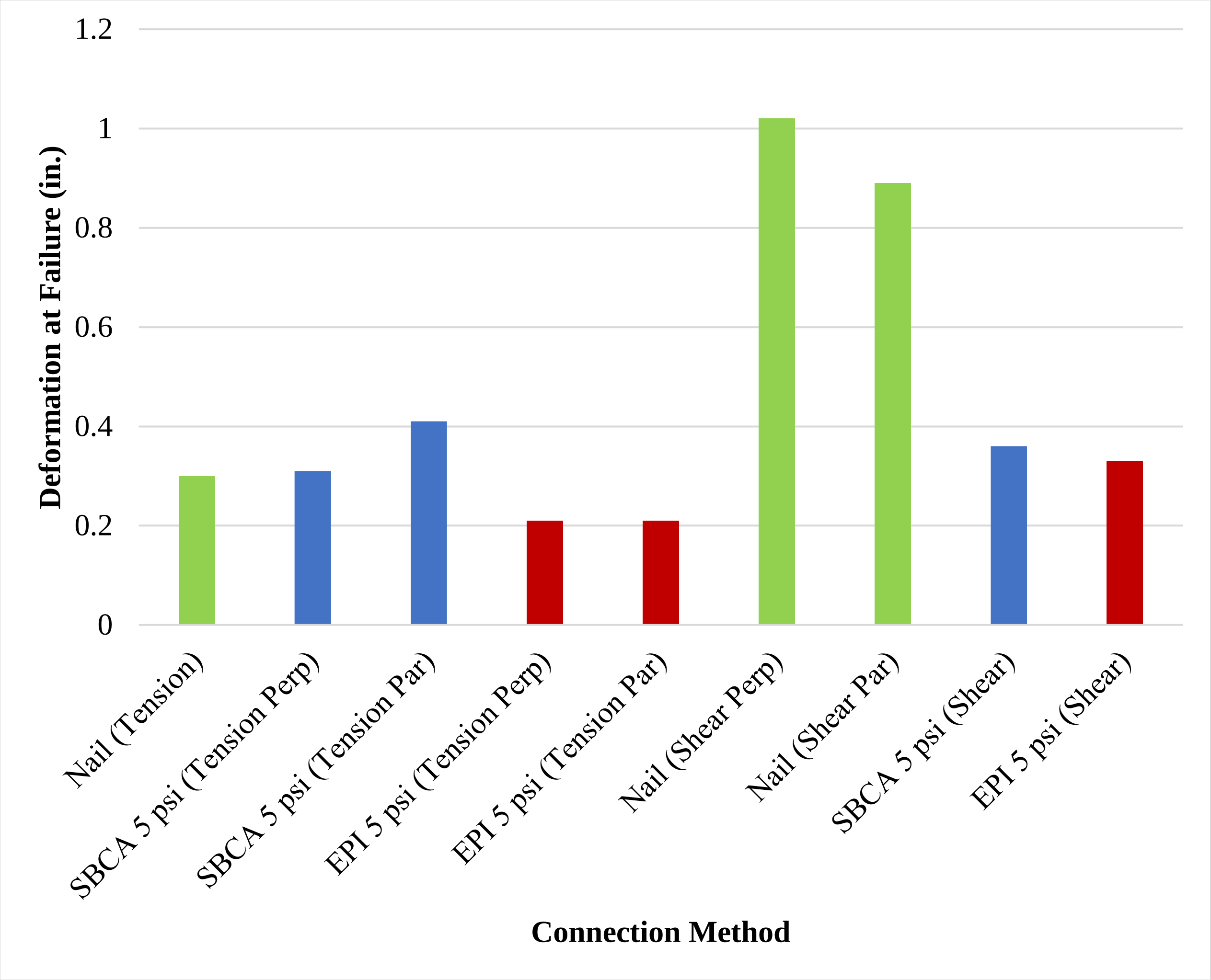


Figure 64. Average deflection at failure for lead deckboard pallet connection using different connection methods

Table 34. Summary table for average energy until failure for lead deckboard pallet connection using different connection methods

Energy Until Failure (ft-lb)				
Connection Method	**Nail**		**Solvent Based Construction Adhesive (SBCA) 5 psi**	**Emulsion Polymer Isocyanate (EPI) 5 psi**
Tension Perpendicular to the Grain	23 (44%) A		24 (29%) A	16 (36%) B
Tension Parallel to the Grain	23 (44%) A		39 (46%) A	10 (66%) C
Shear	**Loaded Perpendicular to the Grain**	**Loaded Parallel to the Grain**	77 (76%) B	76 (96) B
	95 (28%) A	66 (16) B		

Note: Data is presented as average load at failure (lbs.), the numbers in parentheses are Coefficient of Variance values, and statistical analysis presented as groups connected by the same letter not being significantly different based on Wilcoxon tests using alpha 0.05

Due to the high shear strength of the samples that were made with adhesives and the high deformation of samples made with nails, all connection methods tested in shear took larger amounts of energy to reach failure than all connections tested in tension. For samples tested in shear, there was no significant difference between those made with either adhesive to those made with nails when tested with the load parallel to the grain; however nailed samples that had the load applied perpendicular to the grain had significantly higher energy until failure than all other connections. Samples made with the SBCA took equal or higher energy to reach failure than the samples made with nails, and samples made with the two-part EPI adhesive required significantly lower energy to reach failure than either of the other connection methods.

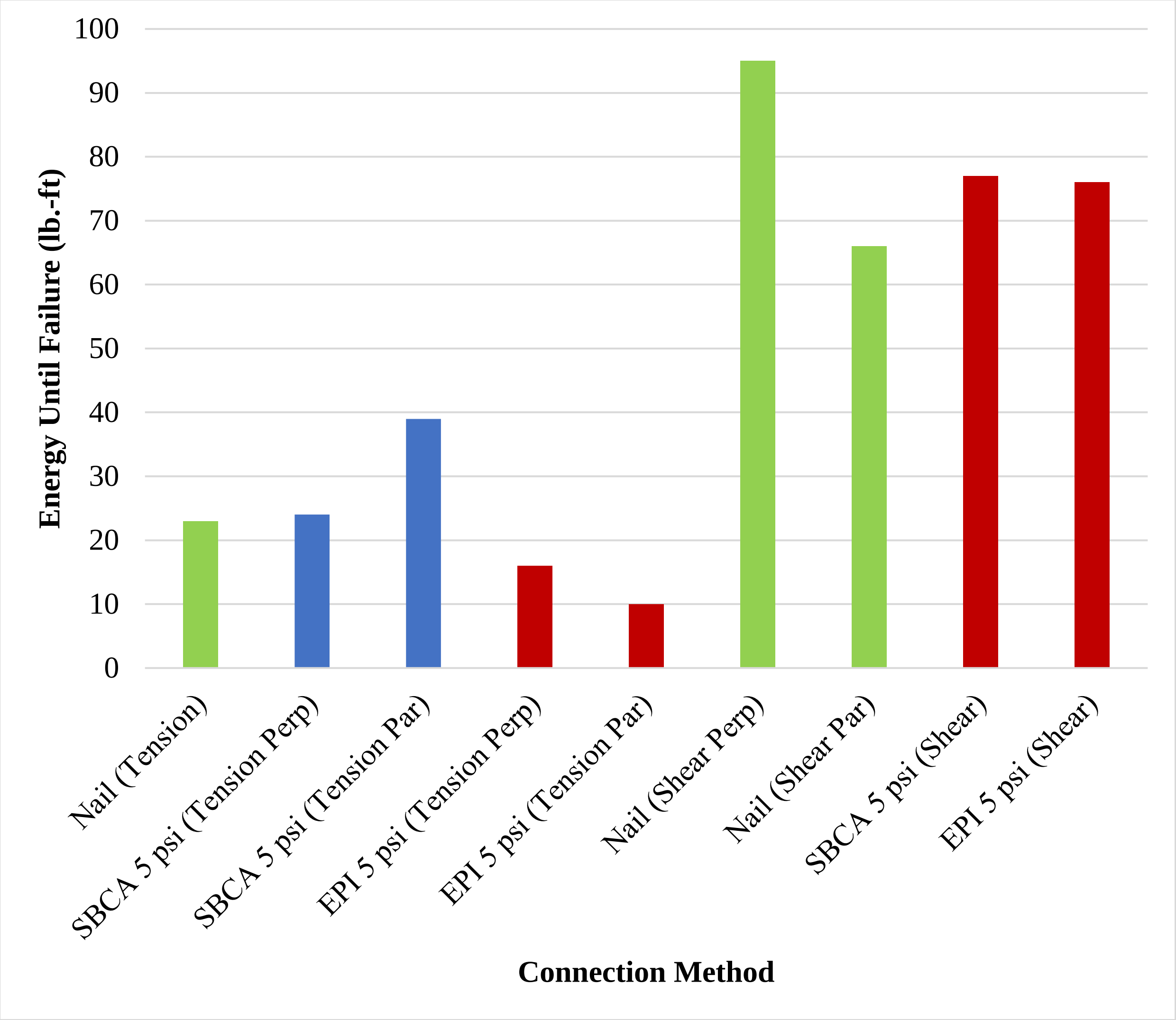


Figure 65. Average energy until failure for lead deckboard pallet connection using different connection methods

Conclusion

The results of the study are resented in the following section:

- The tensile strength, energy required to break the connection, and wood failure increased using tensile testing perpendicular to the grain using samples made with the solvent based construction adhesive (SBCA) increased when curing time was increased to 7+ days from 48 hours, primarily for samples with lower pre-compression pressure. The tensile strength and the energy at failure of the samples were tested after 48 hours and 7+ days and only statistically increased for samples made using lower pre-compressed pressure ranges. The difference of the performance of the samples pre-compressed at a lower pressure range might have been observed because lower pre-compression pressure resulted in a thicker bondline which required a longer curing time.

- Samples made using the SBCA showed a decrease in tensile and shear strength as the pre-compression pressure increased. The strength of samples made with the EPI was not affected by a change in pre-compression pressure. The lack of change in tensile and shear strength could be the result of the low viscosity of the EPI adhesive and the resulting thin bondline.
- In all conditions tested, samples made with the SBCA had a low average amount of wood failure. It also had lower amounts of wood failure than the samples made with the EPI. The exception to this being samples made with the SBCA that were pre-compressed under 5psi that were tested in shear and which failed under compression.

- There is no correlation between the pre-compression pressure and amount of wood failure due to the large amount of variation for both adhesives; however, there was a decrease in average amount of wood failure for the SBCA for tension tests.

- Samples bonded perpendicular to the grain had better performance than samples bonded parallel to the grain when tested in tension.

- Samples made with the SBCA had significantly higher tensile and shear strength and required more energy to reach failure than samples made with nails. Samples made with the EPI had comparable or higher strength than samples made with nails except for tension parallel to the grain tests. Meanwhile, energy required to reach failure for samples made with the EPI was lower or sometimes equal to nailed connections.

- The connections made using 5psi pre-compression pressure and 7+ days curing time showed superior results compared to any other conditions. Using a lower pre-compression pressure could possibly reduce the manufacturing costs due to the lower equipment costs.

This study investigated the performance of pallet connections under controlled conditions. Thus, conditions not investigated, such as wood defects, moisture, weathering, temperature, among other factors could decrease the strength of a connection assembled with adhesives to an unknown extent. The loading rate used is more reflective of a static loading scenario, so it is not a good representation of how the connection would behave during impacts. Therefore, although the adhesives show great potential for use in pallet manufacturing, more investigation is needed to fully understand the behavior of adhesives during real world conditions.

3 Recommendations for Future Research

A cost benefit analysis should be conducted to determine the impact of assembling pallet joints with the solvent based construction adhesive (SBCA) instead of nails on the cost of manufacturing and repair. If it is determined to be beneficial to use adhesives instead of nails based on cost, then further research should be conducted to determine the extent of the capabilities of the SBCA. Connection tests should be conducted to determine if the strength of the connection made with the adhesive would remain equal to or better than the nailed connection when exposed to various conditions seen in pallet use, such as changes in moisture, extreme high and low temperatures, and weathering such as rain or snow. It should also be investigated to what extent a change in surface roughness would lower the strength of the connection. This study looked at connections made with planed lumber, however pallet lumber has a rough surface which could lead to a weaker bond. The adhesive’s resistance to creep and impact should also be investigated. If when exposed to conditions seen in use, connections made with the SBCA remain having similar or better performance than nails, then full size pallets made with both connection methods should be tested.

Factors that affect manufacturing costs should also be investigated so they can be optimized. In this study connections were pre-compressed for 1 hour under various pressures, with the lowest being 5 psi, and allowed to fully cure for 7+ days. The effect of the time that the connection is under pre-compression pressure is unknown and has the potential to be shortened. As the pre-compression pressure decreased for samples made with the SBCA the strength increased. The lowest pre-compression pressure tested was 5 psi, but it is unknown how low the pre-compression pressure can be before the connection loses strength and could be further investigated. Also, while at lower pre-compression pressures there was a significant difference in strength for samples made with the SBCA, but there was not a significant difference at higher pre-compression pressures. This shows that the curing time to reach the full strength, or the necessary strength, could potentially be shorter.

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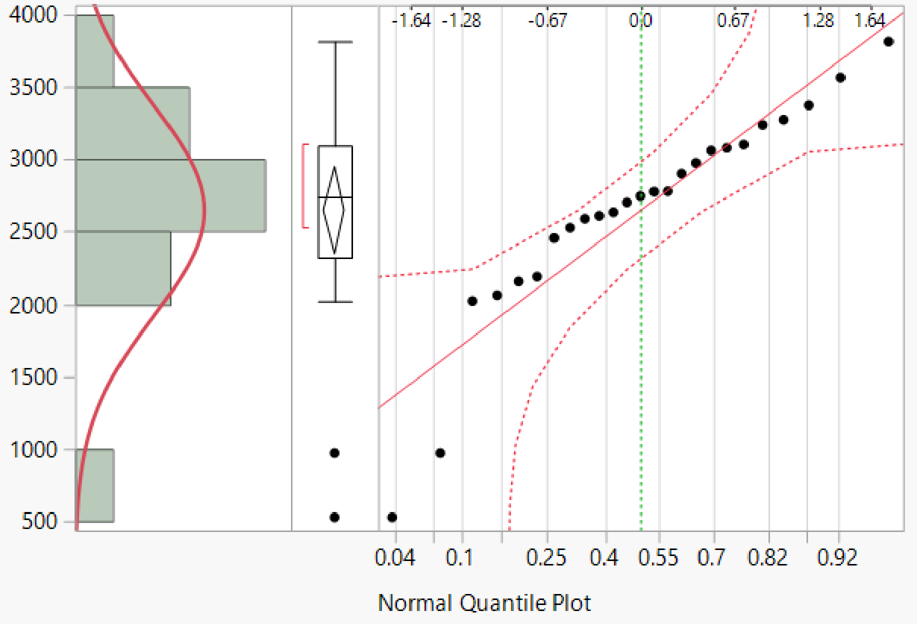
5 Appendix

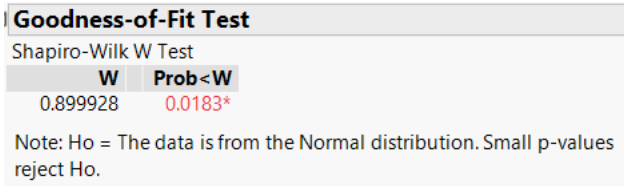
5.1 Appendix A – Statistics for the effect of curing time on the tensile strength perpendicular to the grain of the connection at different pressures using a solvent based construction adhesive

5 psi – 48 Hours:7+ Days – SBCA – Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



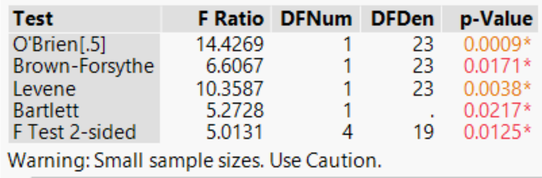
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.899928	0.0183*

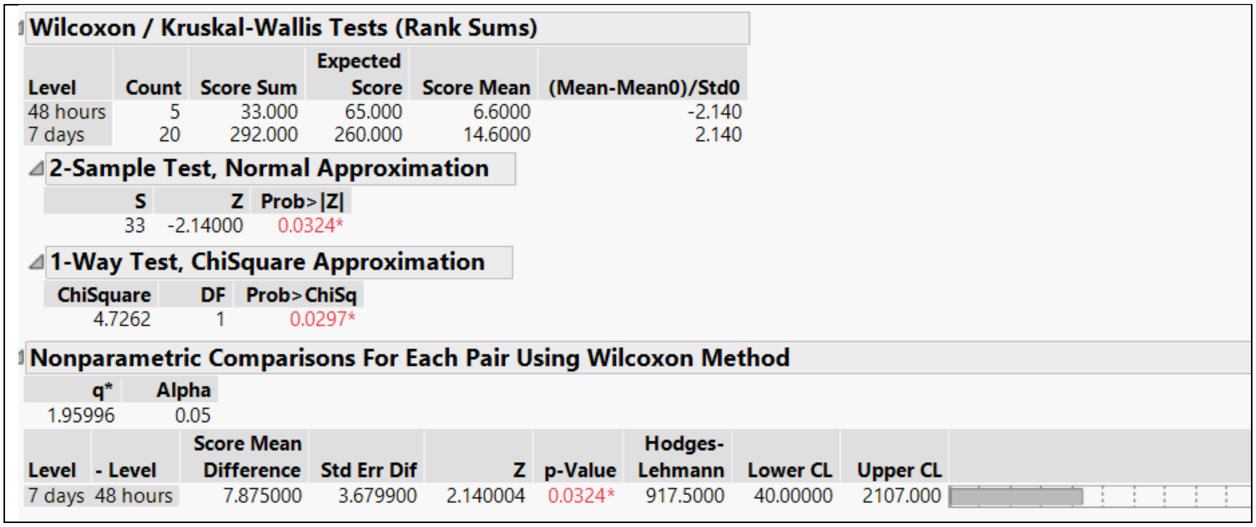
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	14.4269	1	23	0.0009*
Brown-Forsythe	6.6067	1	23	0.0171*
Levene	10.3587	1	23	0.0038*
Bartlett	5.2728	1	.	0.0217*
F Test 2-sided	5.0131	4	19	0.0125*

Warning: Small sample sizes. Use Caution.



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	33.000	65.000	6.6000	-2.140
7 days	20	292.000	260.000	14.6000	2.140

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
33	-2.14000	0.0324*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
4.7262	1	0.0297*

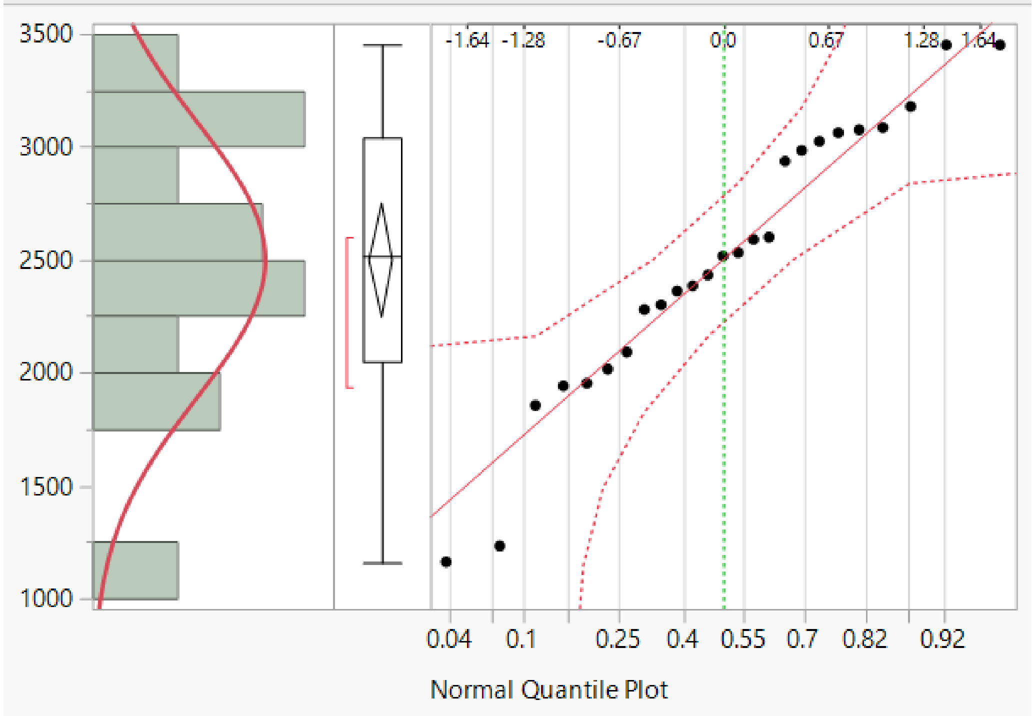
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

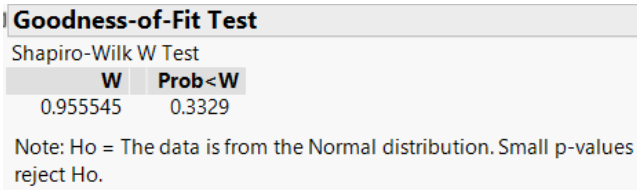
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	7.875000	3.679900	2.140004	0.0324*	917.5000	40.00000	2107.000

25 psi – 48 Hours:7+ Days – SBCA – Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



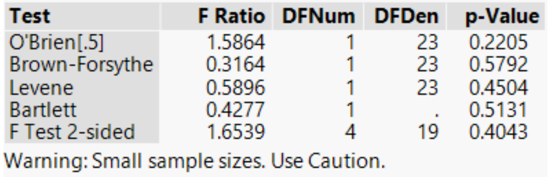
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.955545	0.3329

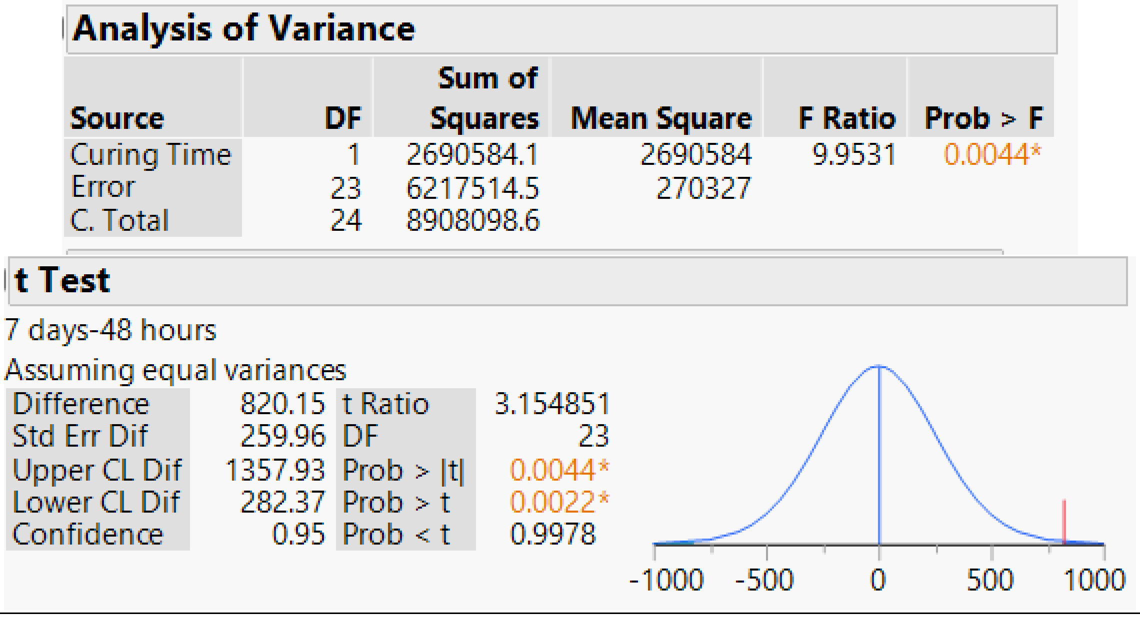
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.5864	1	23	0.2205
Brown-Forsythe	0.3164	1	23	0.5792
Levene	0.5896	1	23	0.4504
Bartlett	0.4277	1	.	0.5131
F Test 2-sided	1.6539	4	19	0.4043

Warning: Small sample sizes. Use Caution.



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	2690584.1	2690584	9.9531	0.0044*
Error	23	6217514.5	270327		
C. Total	24	8908098.6			

t Test

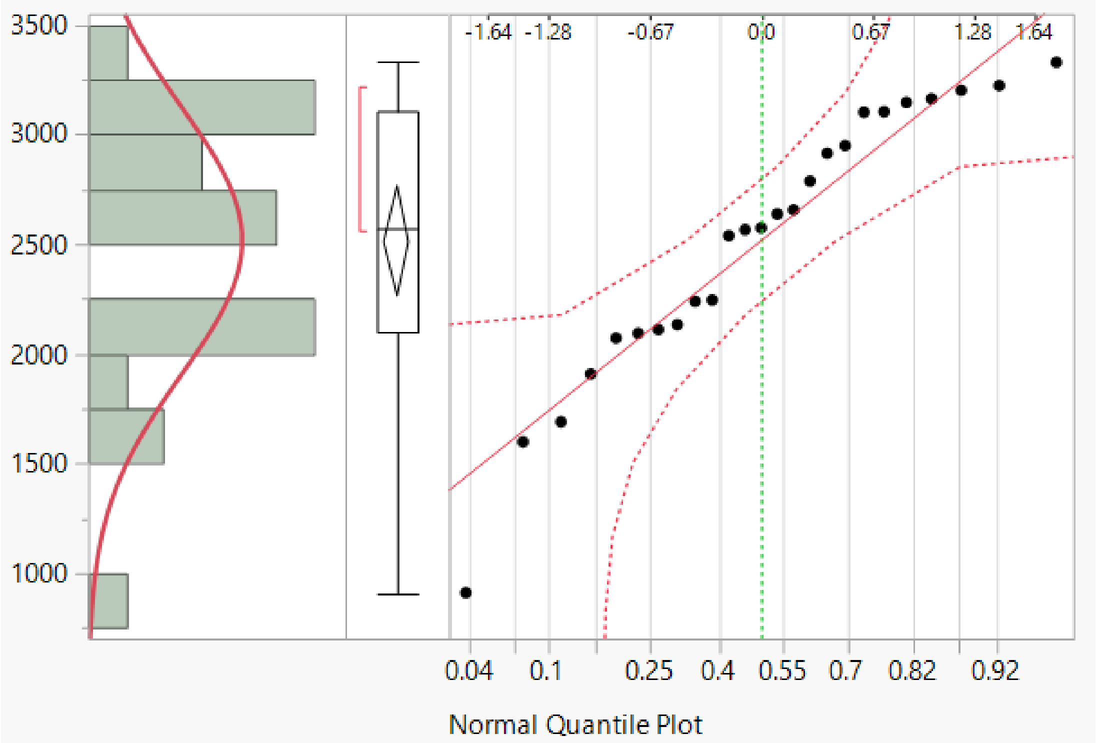
7 days-48 hours

Assuming equal variances

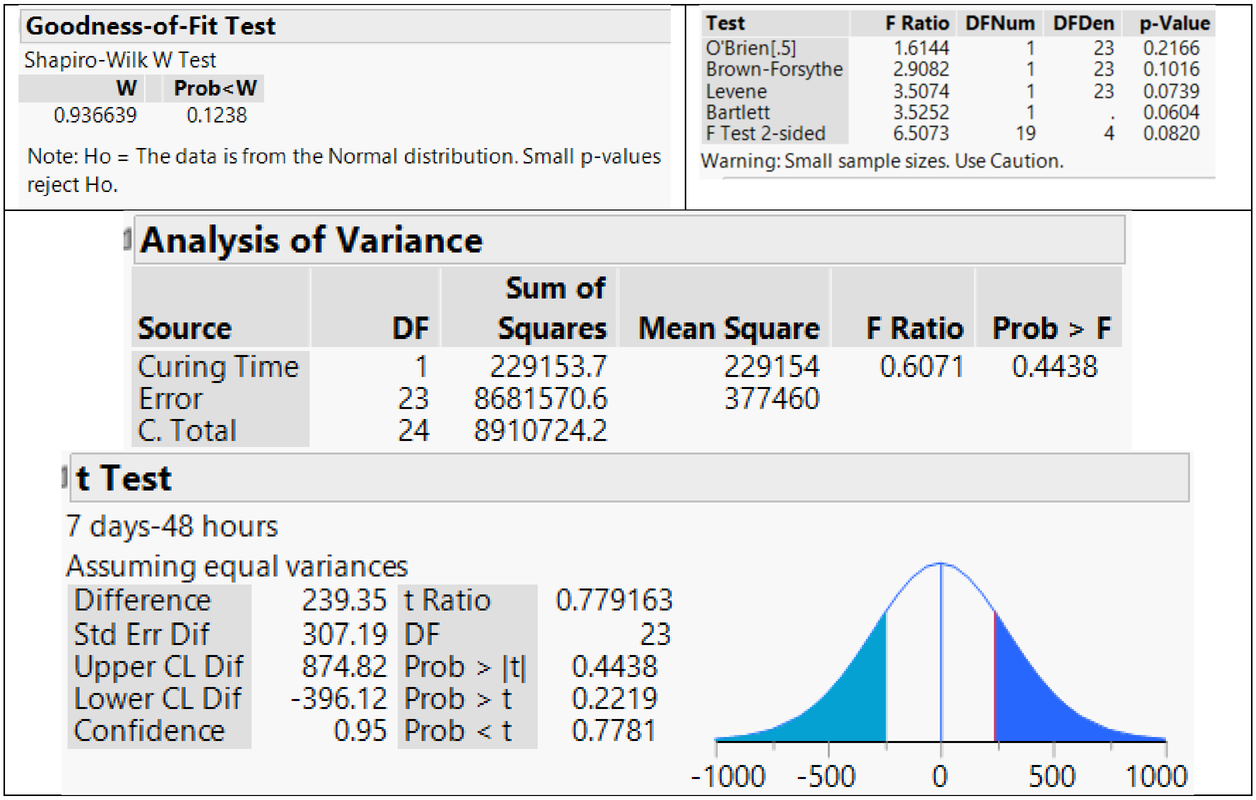
Difference	820.15	t Ratio	3.154851
Std Err Dif	259.96	DF	23
Upper CL Dif	1357.93	Prob > |t|	0.0044*
Lower CL Dif	282.37	Prob > t	0.0022*
Confidence	0.95	Prob < t	0.9978

50 psi – 48 Hours:7+ Days – SBCA – Load at Failure

Distribution & Normal quantile plot



Goodness of Fit	Variances



Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.936639	0.1238

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.6144	1	23	0.2166
Brown-Forsythe	2.9082	1	23	0.1016
Levene	3.5074	1	23	0.0739
Bartlett	3.5252	1	.	0.0604
F Test 2-sided	6.5073	19	4	0.0820

Warning: Small sample sizes. Use Caution.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	229153.7	229154	0.6071	0.4438
Error	23	8681570.6	377460		
C. Total	24	8910724.2			

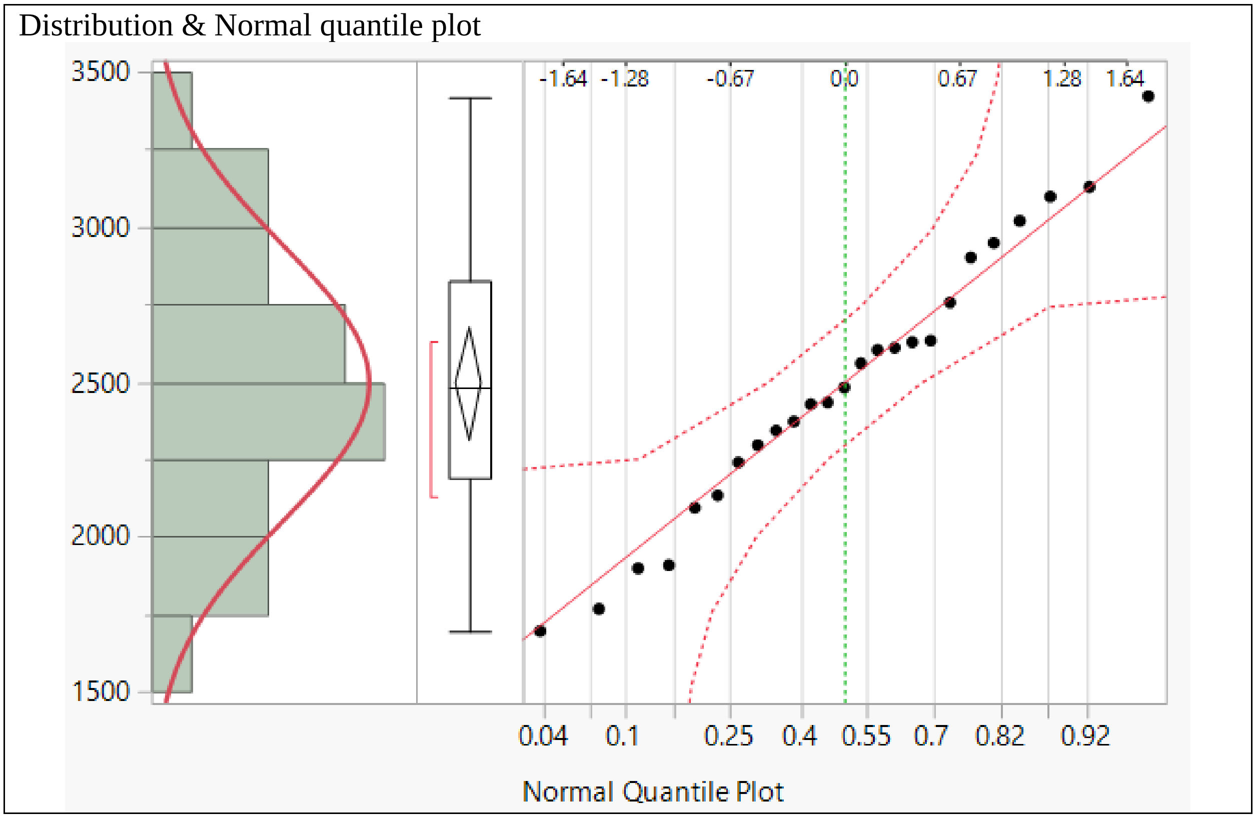
t Test

7 days-48 hours

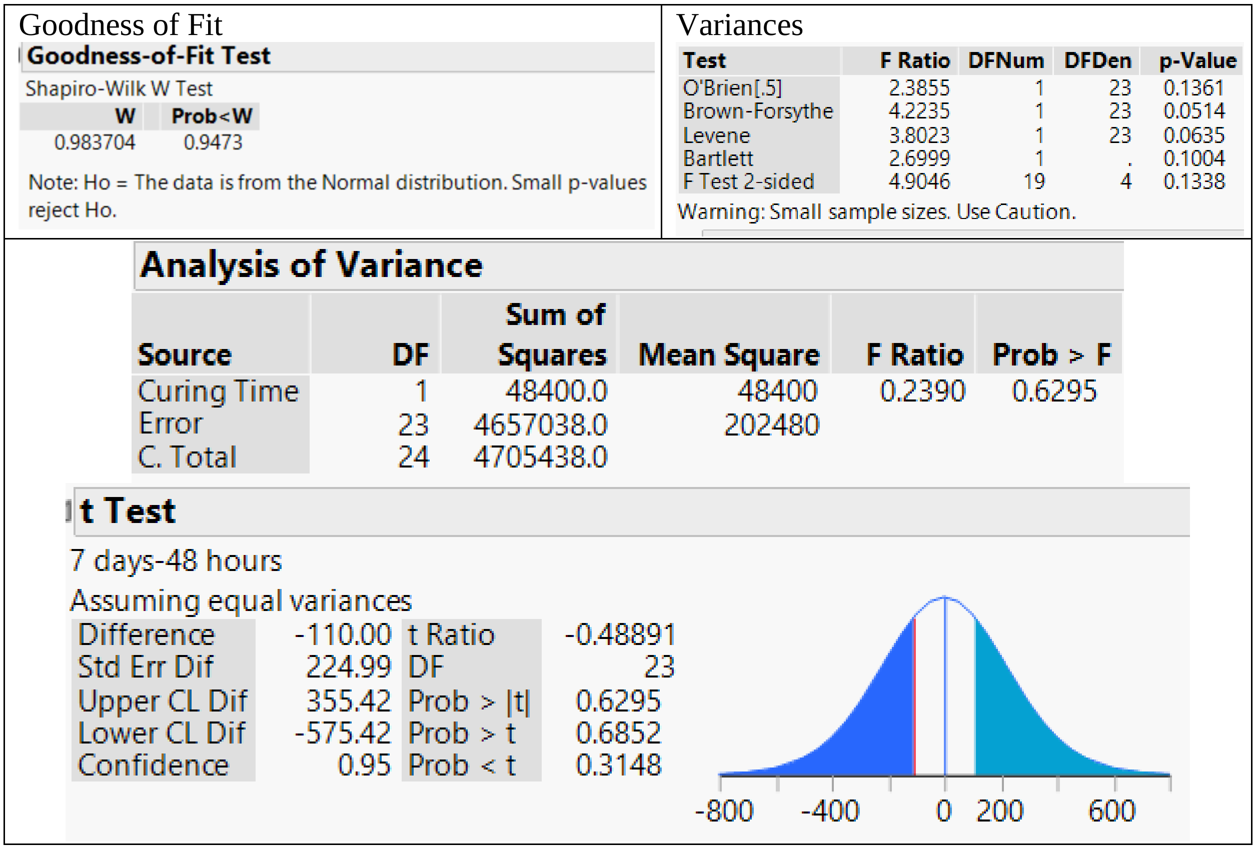
Assuming equal variances

Difference	239.35	t Ratio	0.779163
Std Err Dif	307.19	DF	23
Upper CL Dif	874.82	Prob > |t|	0.4438
Lower CL Dif	-396.12	Prob > t	0.2219
Confidence	0.95	Prob < t	0.7781

75 psi – 48 Hours:7+ Days – SBCA – Load at Failure



Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.983704	0.9473

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.3855	1	23	0.1361
Brown-Forsythe	4.2235	1	23	0.0514
Levene	3.8023	1	23	0.0635
Bartlett	2.6999	1	.	0.1004
F Test 2-sided	4.9046	19	4	0.1338

Warning: Small sample sizes. Use Caution.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	48400.0	48400	0.2390	0.6295
Error	23	4657038.0	202480		
C. Total	24	4705438.0			

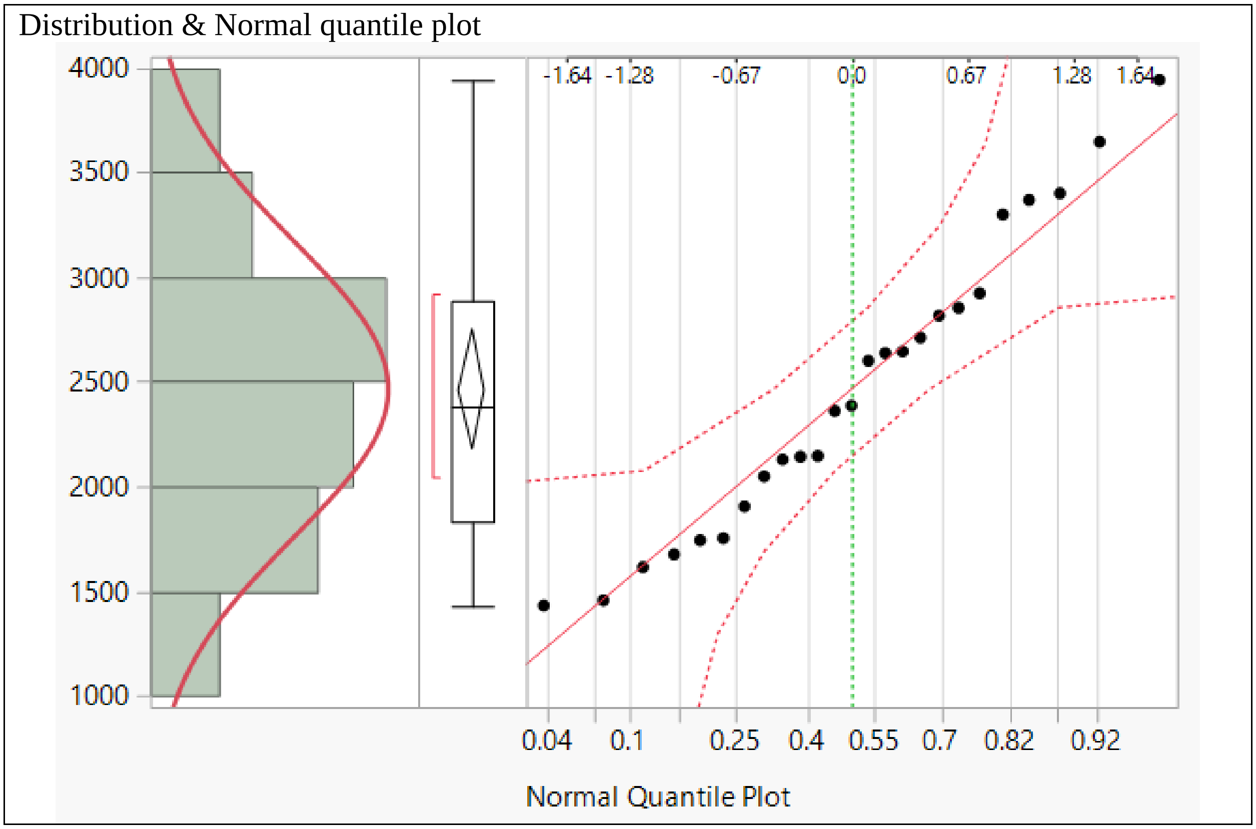
t Test

7 days-48 hours

Assuming equal variances

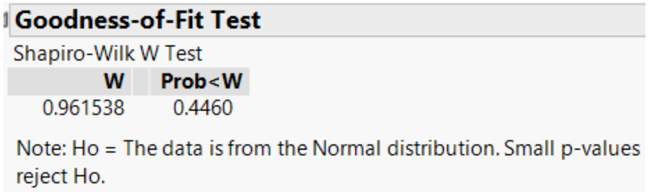
Difference	-110.00	t Ratio	-0.48891
Std Err Dif	224.99	DF	23
Upper CL Dif	355.42	Prob > |t|	0.6295
Lower CL Dif	-575.42	Prob > t	0.6852
Confidence	0.95	Prob < t	0.3148

100 psi – 48 Hours:7+ Days – SBCA – Load at Failure



Distribution & Normal quantile plot

Goodness of Fit



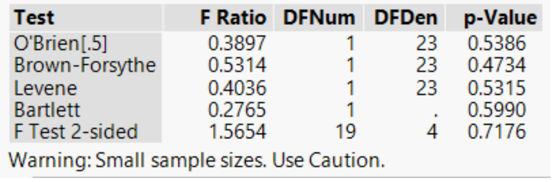
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.961538	0.4460

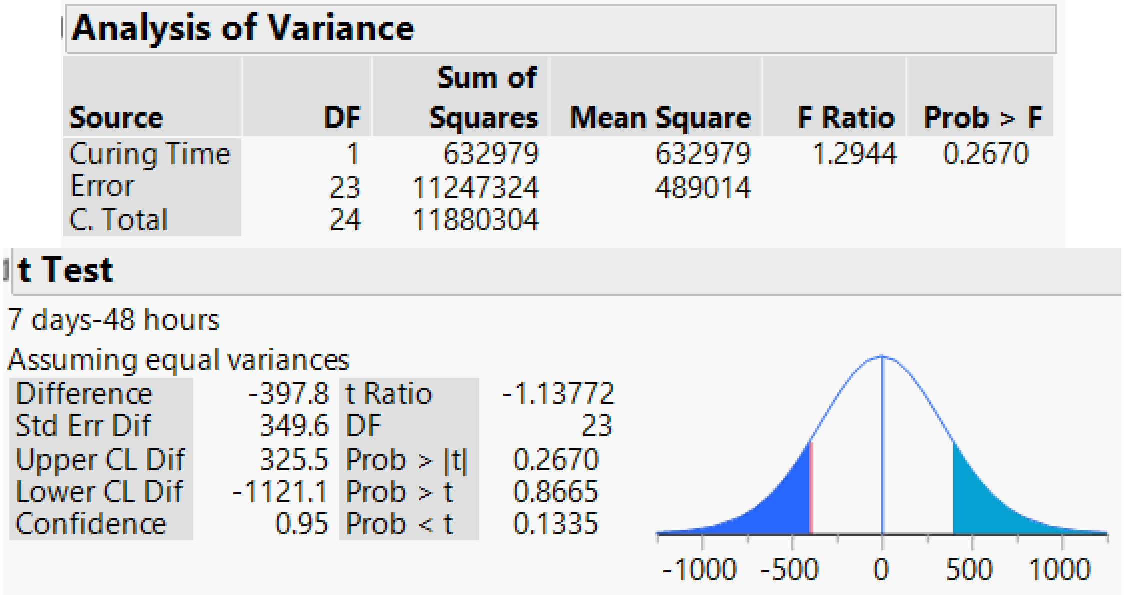
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.3897	1	23	0.5386
Brown-Forsythe	0.5314	1	23	0.4734
Levene	0.4036	1	23	0.5315
Bartlett	0.2765	1	.	0.5990
F Test 2-sided	1.5654	19	4	0.7176

Warning: Small sample sizes. Use Caution.



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	632979	632979	1.2944	0.2670
Error	23	11247324	489014		
C. Total	24	11880304			

t Test

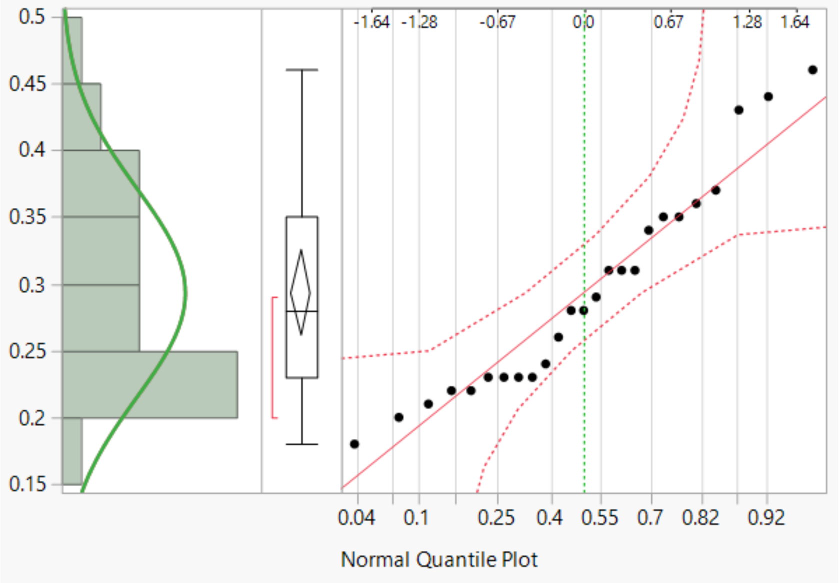
7 days-48 hours

Assuming equal variances

Difference	-397.8	t Ratio	-1.13772
Std Err Dif	349.6	DF	23
Upper CL Dif	325.5	Prob > |t|	0.2670
Lower CL Dif	-1121.1	Prob > t	0.8665
Confidence	0.95	Prob < t	0.1335

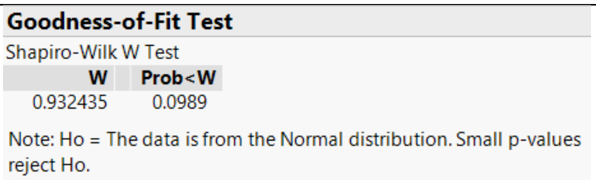
5 psi – 48 Hours:7+ Days – SBCA – Deformation at Failure

Distribution & Normal Quantile Plot



Goodness of Fit

Variances

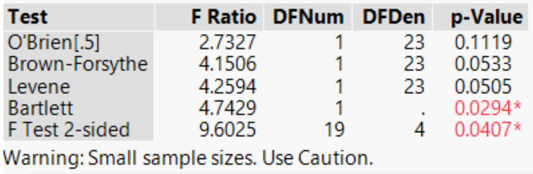


Goodness-of-Fit Test

Shapiro-Wilk W Test

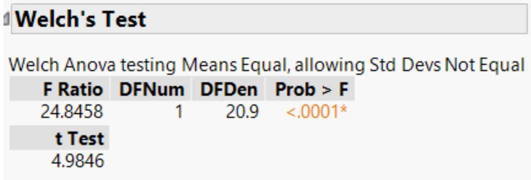
W	Prob<W
0.932435	0.0989

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.



Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.7327	1	23	0.1119
Brown-Forsythe	4.1506	1	23	0.0533
Levene	4.2594	1	23	0.0505
Bartlett	4.7429	1	.	0.0294*
F Test 2-sided	9.6025	19	4	0.0407*

Warning: Small sample sizes. Use Caution.

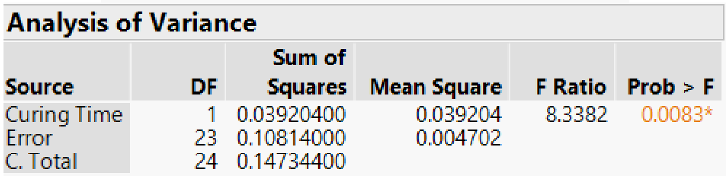


Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

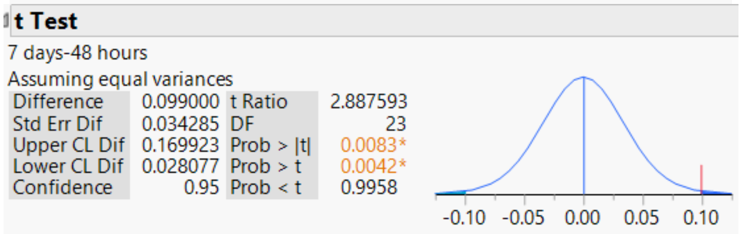
F Ratio	DFNum	DFDen	Prob > F
24.8458	1	20.9	<.0001*

t Test
4.9846



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	0.03920400	0.039204	8.3382	0.0083*
Error	23	0.10814000	0.004702		
C. Total	24	0.14734400			

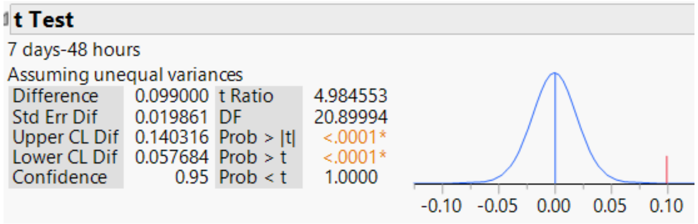


t Test

7 days-48 hours

Assuming equal variances

Difference	0.099000	t Ratio	2.887593
Std Err Dif	0.034285	DF	23
Upper CL Dif	0.169923	Prob > |t|	0.0083*
Lower CL Dif	0.028077	Prob > t	0.0042*
Confidence	0.95	Prob < t	0.9958



t Test

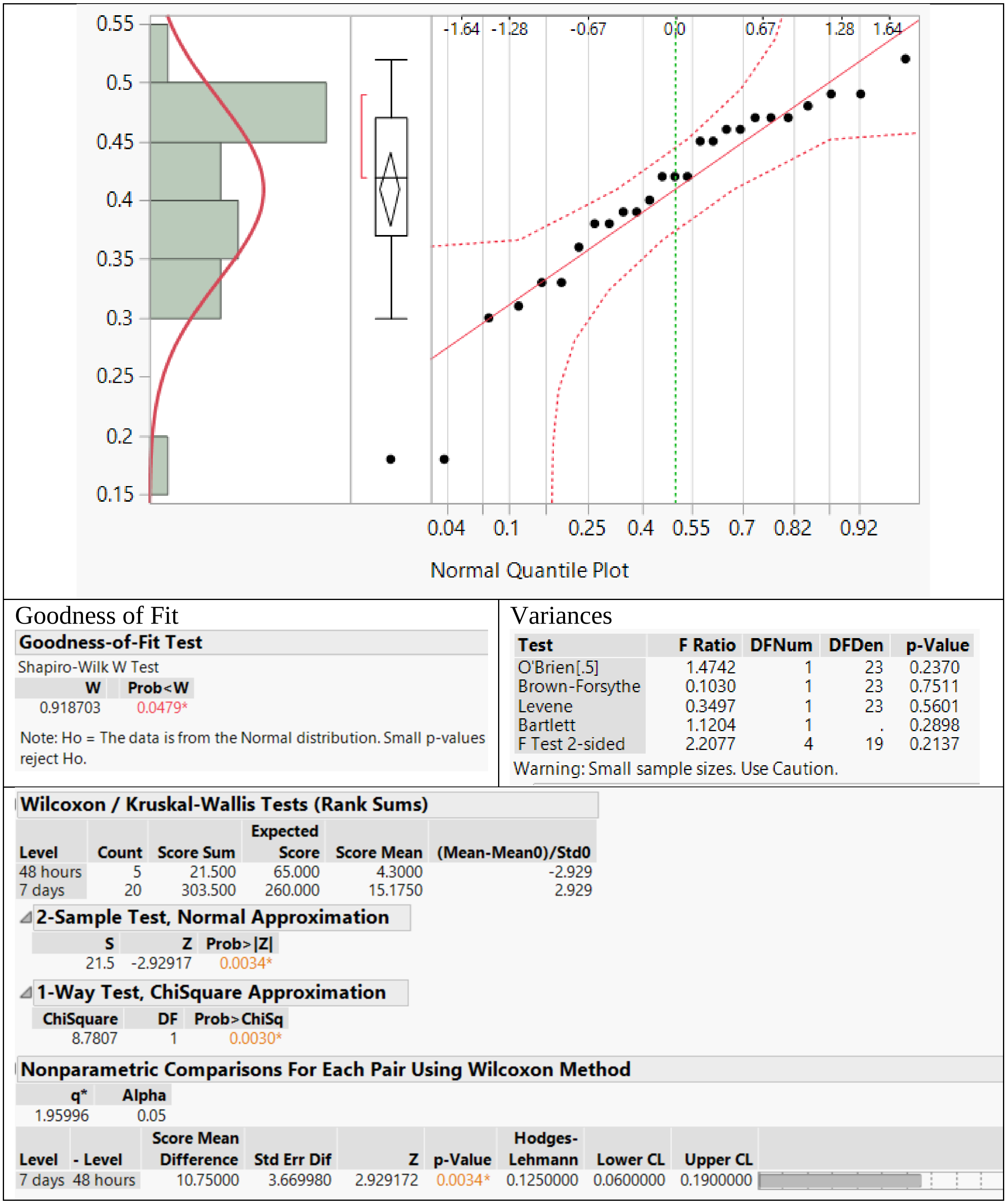
7 days-48 hours

Assuming unequal variances

Difference	0.099000	t Ratio	4.984553
Std Err Dif	0.019861	DF	20.89994
Upper CL Dif	0.140316	Prob > |t|	<.0001*
Lower CL Dif	0.057684	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

25 psi – 48 Hours:7+ Days – SBCA – Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.918703	0.0479*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.4742	1	23	0.2370
Brown-Forsythe	0.1030	1	23	0.7511
Levene	0.3497	1	23	0.5601
Bartlett	1.1204	1	.	0.2898
F Test 2-sided	2.2077	4	19	0.2137

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	21.500	65.000	4.3000	-2.929
7 days	20	303.500	260.000	15.1750	2.929

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
21.5	-2.92917	0.0034*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
8.7807	1	0.0030*

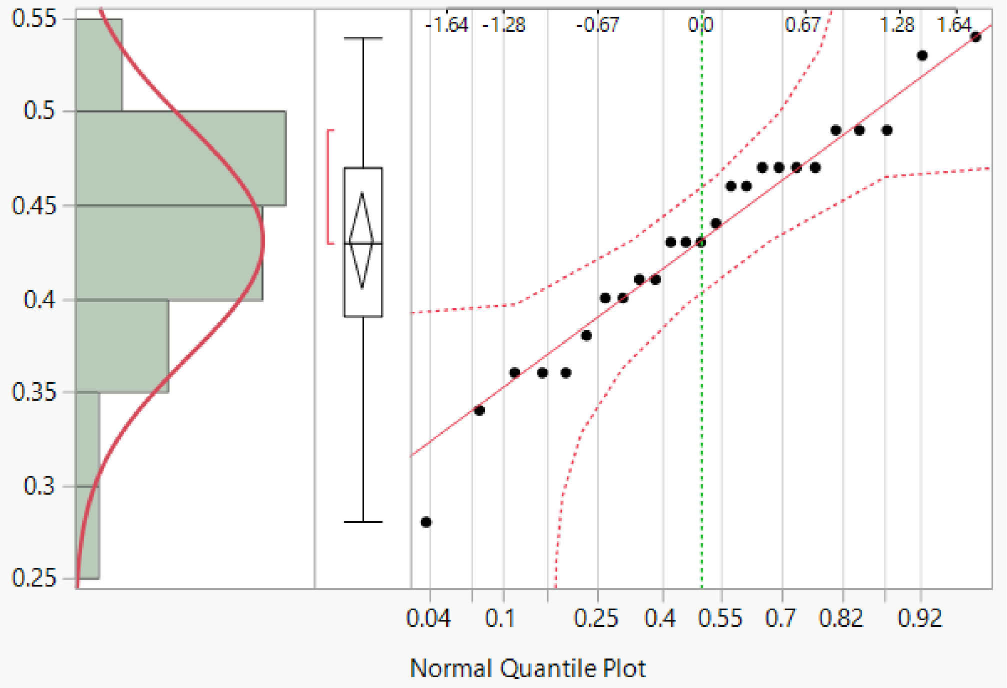
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	10.75000	3.669980	2.929172	0.0034*	0.1250000	0.0600000	0.1900000

50 psi – 48 Hours:7+ Days – SBCA – Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.971783	0.6905

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	3.1406	1	23	0.0896
Brown-Forsythe	1.2186	1	23	0.2810
Levene	1.6709	1	23	0.2090
Bartlett	1.1623	1	.	0.2810
F Test 2-sided	2.2381	4	19	0.2065

Warning: Small sample sizes. Use Caution.

Analysis of Variance

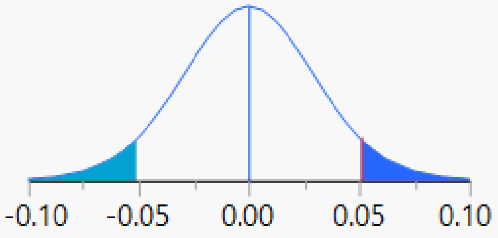
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	0.01040400	0.010404	2.9477	0.0994
Error	23	0.08118000	0.003530		
C. Total	24	0.09158400			

t Test

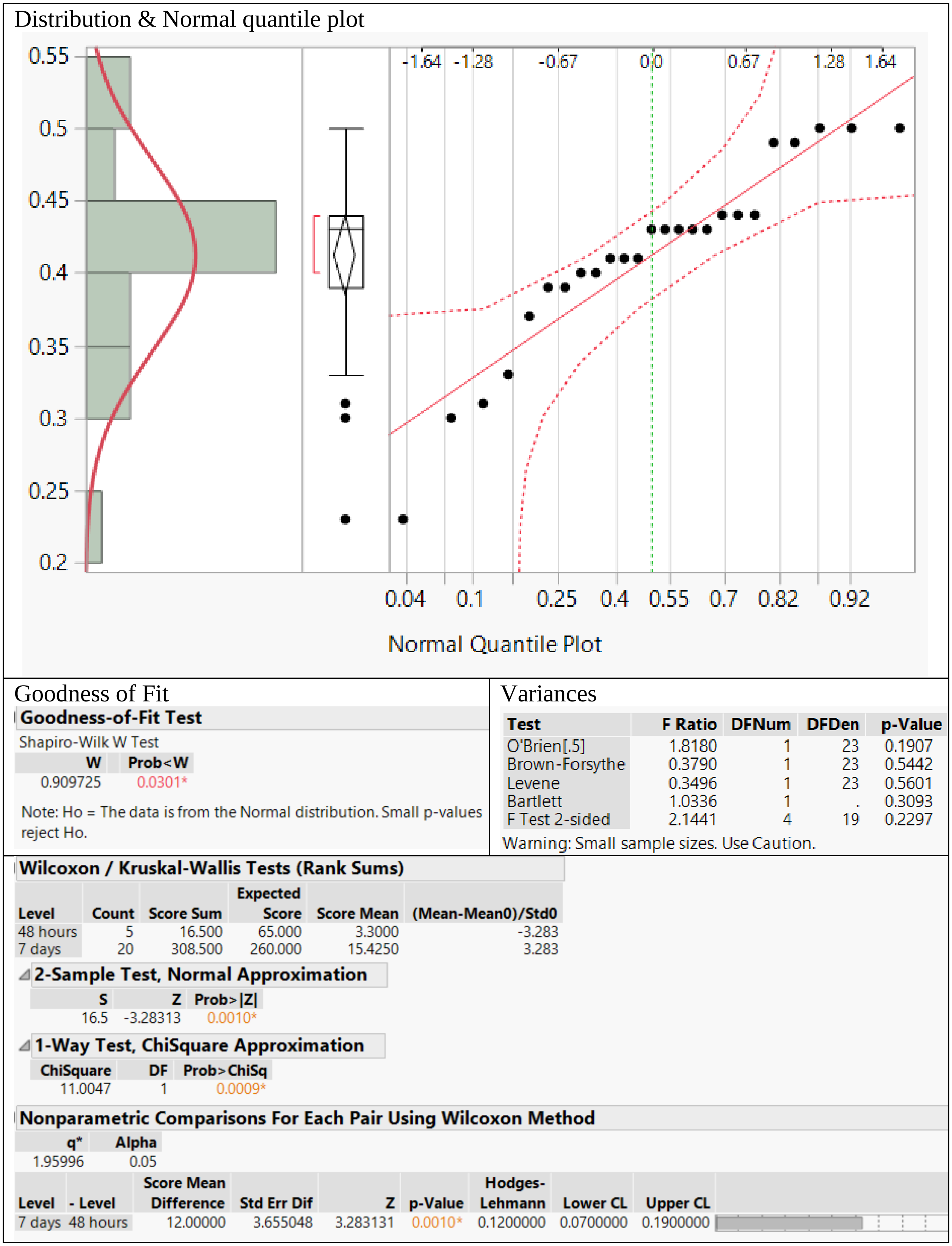
7 days-48 hours

Assuming equal variances

Difference	0.05100	t Ratio	1.716879
Std Err Dif	0.02971	DF	23
Upper CL Dif	0.11245	Prob > |t|	0.0994
Lower CL Dif	-0.01045	Prob > t	0.0497*
Confidence	0.95	Prob < t	0.9503



75 psi – 48 Hours:7+ Days – SBCA – Deformation at Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.909725	0.0301*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.8180	1	23	0.1907
Brown-Forsythe	0.3790	1	23	0.5442
Levene	0.3496	1	23	0.5601
Bartlett	1.0336	1	.	0.3093
F Test 2-sided	2.1441	4	19	0.2297

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	16.500	65.000	3.3000	-3.283
7 days	20	308.500	260.000	15.4250	3.283

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
16.5	-3.28313	0.0010*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
11.0047	1	0.0009*

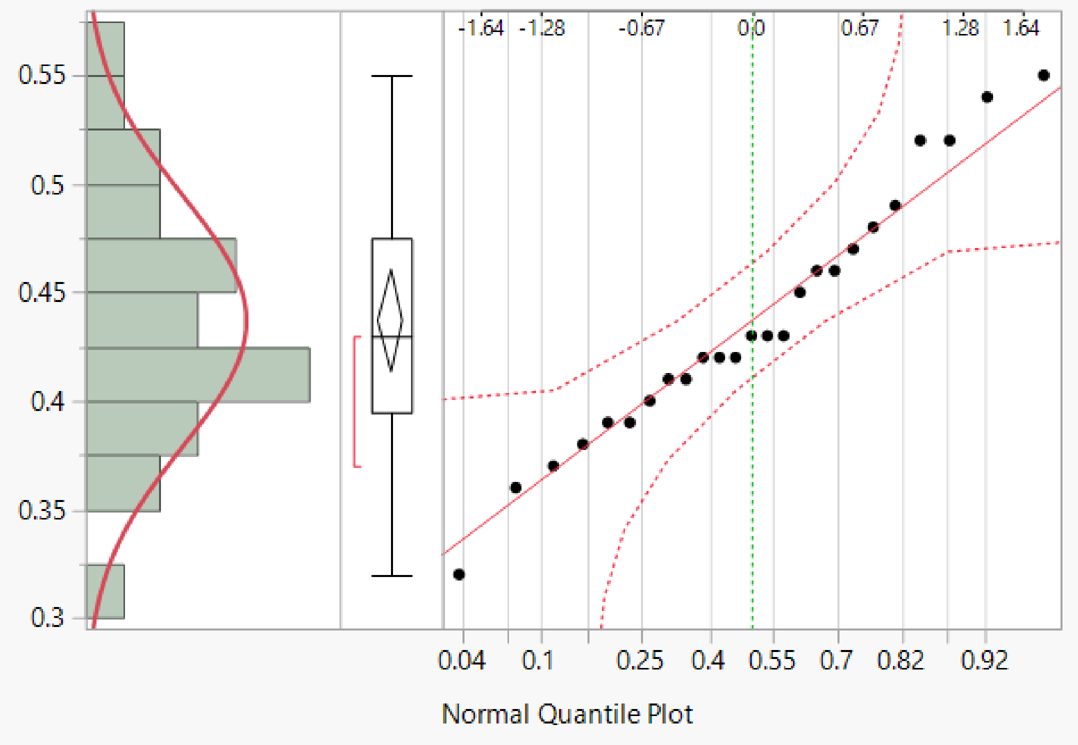
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	12.00000	3.655048	3.283131	0.0010*	0.1200000	0.0700000	0.1900000

100 psi – 48 Hours:7+ Days – SBCA – Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.974591	0.7616

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.4392	1	23	0.1320
Brown-Forsythe	1.0036	1	23	0.3269
Levene	1.3471	1	23	0.2577
Bartlett	1.2192	1	.	0.2695
F Test 2-sided	2.2790	4	19	0.1971

Warning: Small sample sizes. Use Caution.

Analysis of Variance

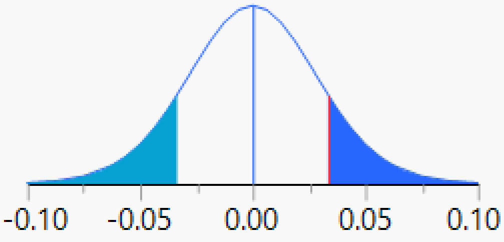
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	0.00448900	0.004489	1.3720	0.2535
Error	23	0.07525500	0.003272		
C. Total	24	0.07974400			

t Test

7 days-48 hours

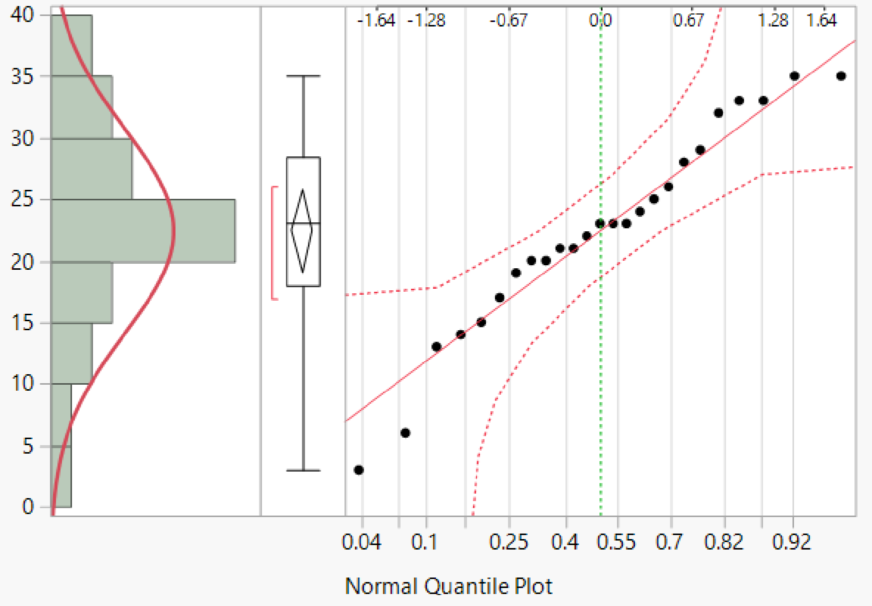
Assuming equal variances

Difference	0.03350	t Ratio	1.171308
Std Err Dif	0.02860	DF	23
Upper CL Dif	0.09266	Prob > |t|	0.2535
Lower CL Dif	-0.02566	Prob > t	0.1267
Confidence	0.95	Prob < t	0.8733



5 psi – 48 Hours:7+ Days – SBCA – Energy

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.959442	0.4035

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	6.1449	1	23	0.0209*
Brown-Forsythe	1.3061	1	23	0.2649
Levene	3.8200	1	23	0.0629
Bartlett	1.5494	1	.	0.2132
F Test 2-sided	2.5108	4	19	0.1521

Warning: Small sample sizes. Use Caution.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	240.2500	240.250	3.9252	0.0596
Error	23	1407.7500	61.207		
C. Total	24	1648.0000			

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
2.2442	1	4.8262	0.1964

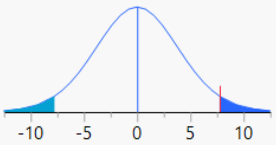
t Test
1.4981

t Test

7 days-48 hours

Assuming equal variances

Difference	7.750	t Ratio	1.981221
Std Err Dif	3.912	DF	23
Upper CL Dif	15.842	Prob > |t|	0.0596
Lower CL Dif	-0.342	Prob > t	0.0298*
Confidence	0.95	Prob < t	0.9702

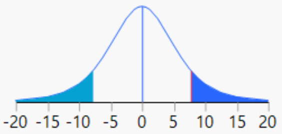


t Test

7 days-48 hours

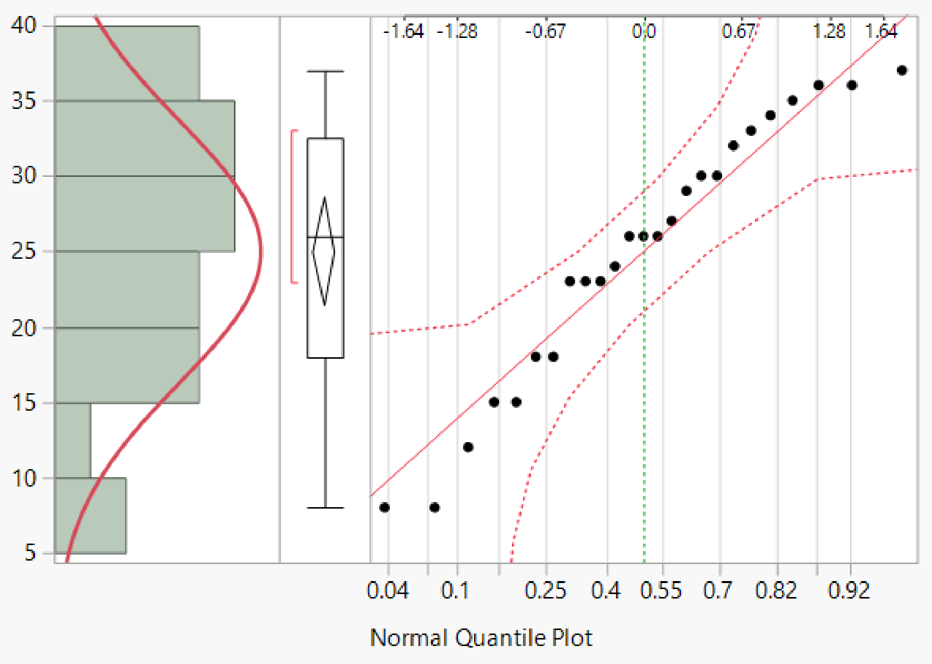
Assuming unequal variances

Difference	7.750	t Ratio	1.498062
Std Err Dif	5.173	DF	4.82615
Upper CL Dif	21.194	Prob > |t|	0.1964
Lower CL Dif	-5.694	Prob > t	0.0982
Confidence	0.95	Prob < t	0.9018

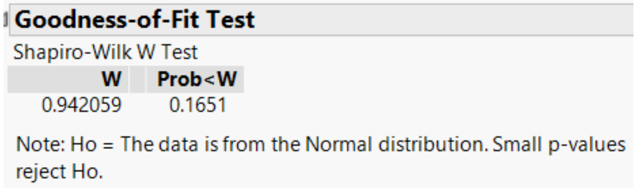


25 psi – 48 Hours:7+ Days – SBCA – Energy

Distribution & Normal quantile plot



Goodness of Fit



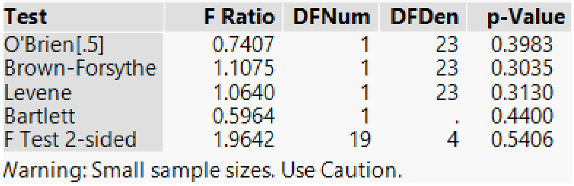
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.942059	0.1651

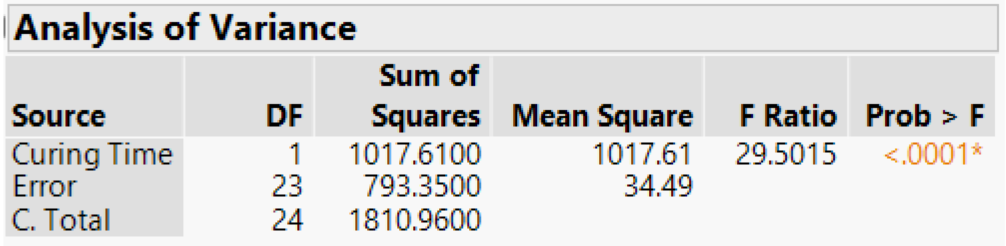
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



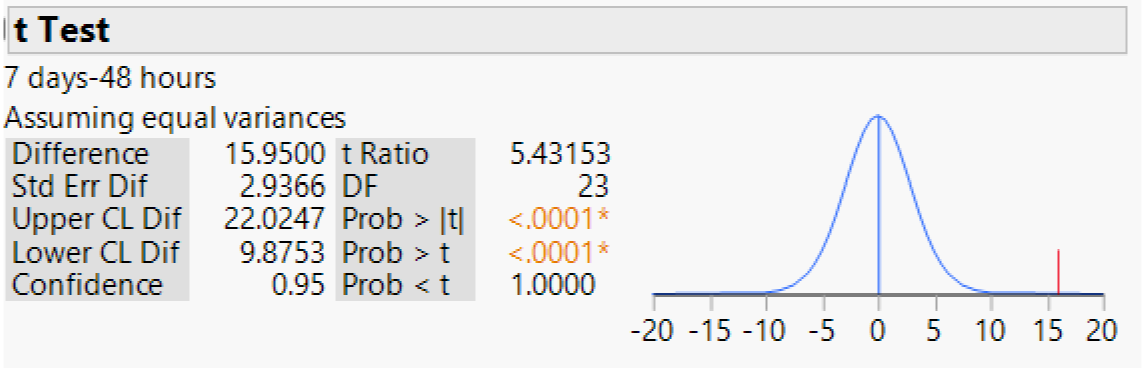
Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.7407	1	23	0.3983
Brown-Forsythe	1.1075	1	23	0.3035
Levene	1.0640	1	23	0.3130
Bartlett	0.5964	1	.	0.4400
F Test 2-sided	1.9642	19	4	0.5406

Warning: Small sample sizes. Use Caution.



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	1017.6100	1017.61	29.5015	<.0001*
Error	23	793.3500	34.49		
C. Total	24	1810.9600			



t Test

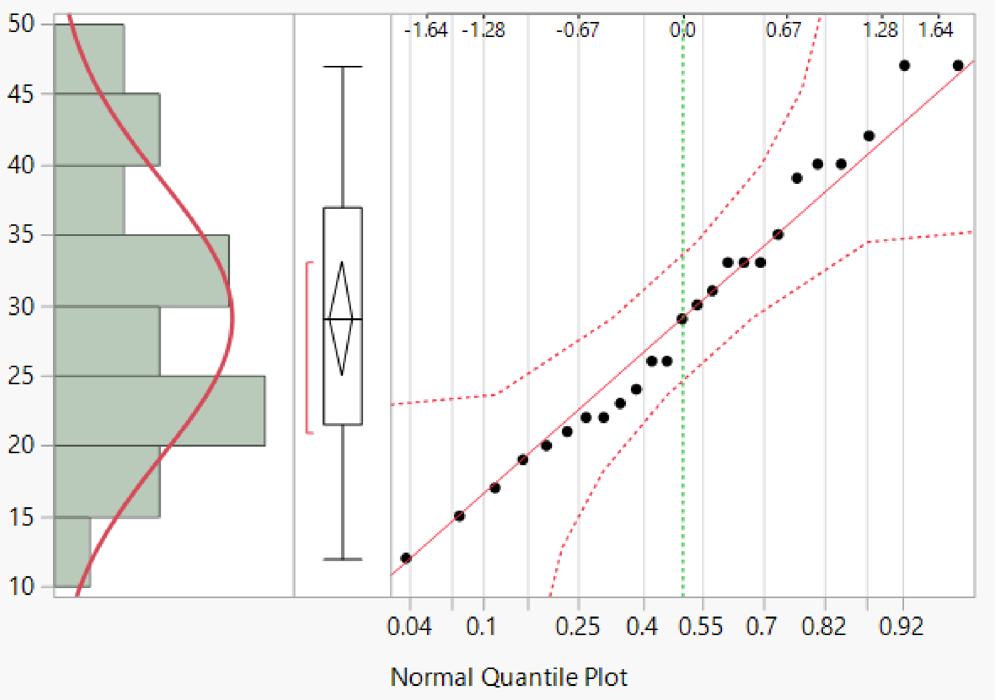
7 days-48 hours

Assuming equal variances

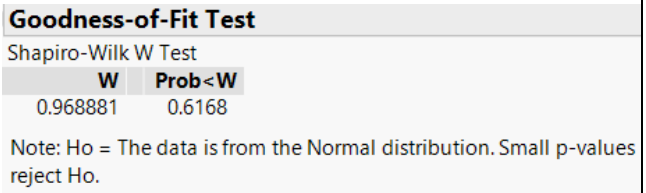
Difference	15.9500	t Ratio	5.43153
Std Err Dif	2.9366	DF	23
Upper CL Dif	22.0247	Prob > |t|	<.0001*
Lower CL Dif	9.8753	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

50 psi – 48 Hours:7+ Days – SBCA – Energy

Distribution & Normal quantile plot



Goodness of Fit



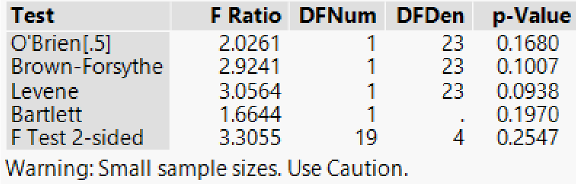
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.968881	0.6168

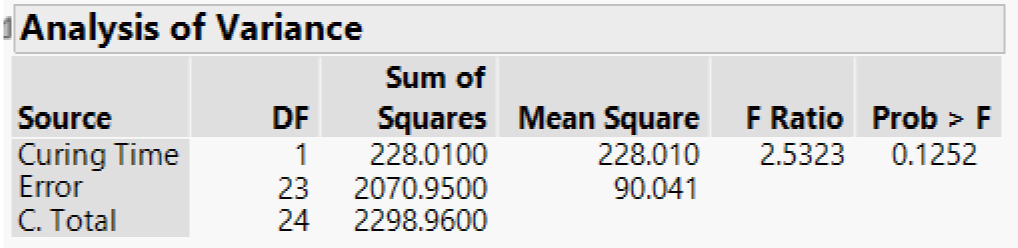
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



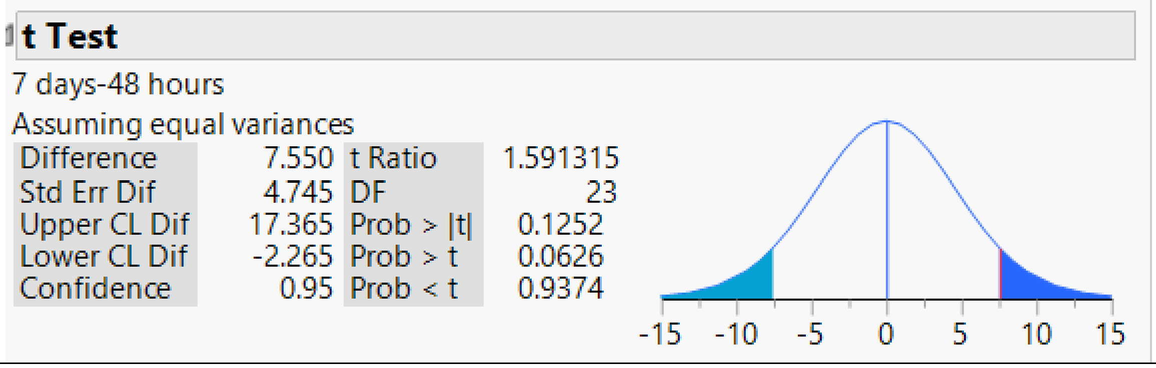
Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.0261	1	23	0.1680
Brown-Forsythe	2.9241	1	23	0.1007
Levene	3.0564	1	23	0.0938
Bartlett	1.6644	1	.	0.1970
F Test 2-sided	3.3055	19	4	0.2547

Warning: Small sample sizes. Use Caution.



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	228.0100	228.010	2.5323	0.1252
Error	23	2070.9500	90.041		
C. Total	24	2298.9600			



t Test

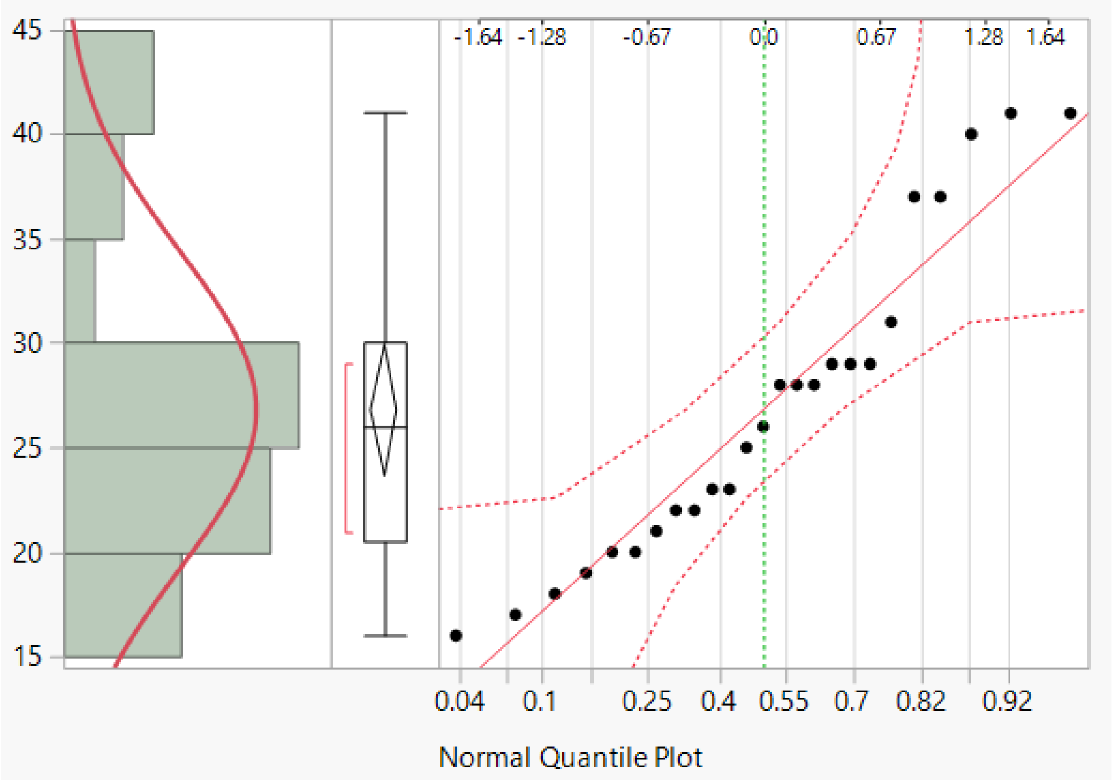
7 days-48 hours

Assuming equal variances

Difference	7.550	t Ratio	1.591315
Std Err Dif	4.745	DF	23
Upper CL Dif	17.365	Prob > |t|	0.1252
Lower CL Dif	-2.265	Prob > t	0.0626
Confidence	0.95	Prob < t	0.9374

75 psi – 48 Hours:7+ Days – SBCA – Energy

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.923925	0.0630

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.5371	1	23	0.1249
Brown-Forsythe	2.2507	1	23	0.1472
Levene	2.0583	1	23	0.1648
Bartlett	2.4414	1	.	0.1182
F Test 2-sided	4.4677	19	4	0.1565

Warning: Small sample sizes. Use Caution.

Analysis of Variance

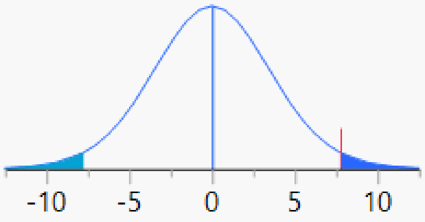
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Curing Time	1	240.2500	240.250	4.8567	0.0378*
Error	23	1137.7500	49.467		
C. Total	24	1378.0000			

t Test

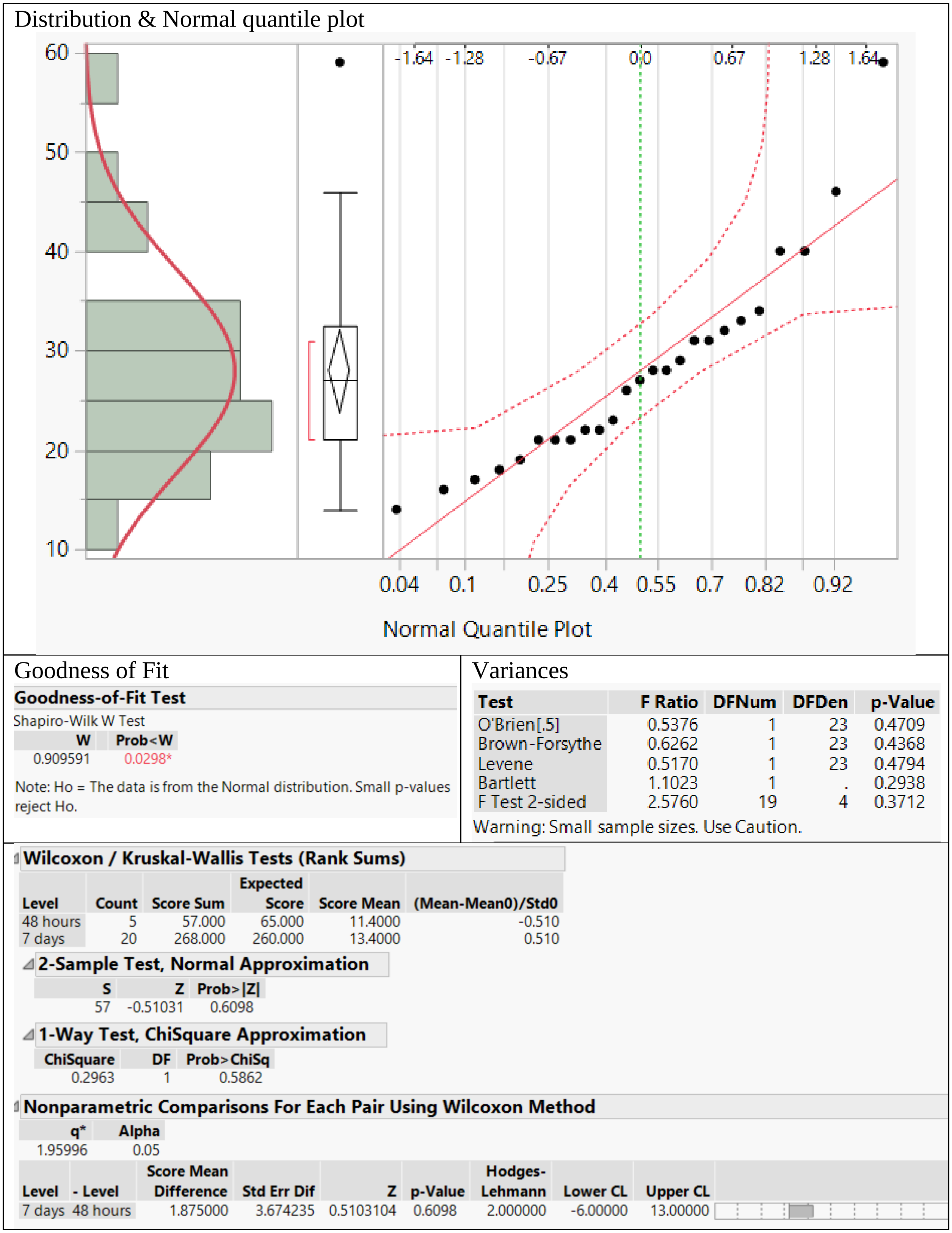
7 days-48 hours

Assuming equal variances

Difference	7.7500	t Ratio	2.2038
Std Err Dif	3.5167	DF	23
Upper CL Dif	15.0248	Prob > |t|	0.0378*
Lower CL Dif	0.4752	Prob > t	0.0189*
Confidence	0.95	Prob < t	0.9811



100 psi – 48 Hours:7+ Days – SBCA – Energy



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.909591	0.0298*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.5376	1	23	0.4709
Brown-Forsythe	0.6262	1	23	0.4368
Levene	0.5170	1	23	0.4794
Bartlett	1.1023	1	.	0.2938
F Test 2-sided	2.5760	19	4	0.3712

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	57.000	65.000	11.4000	-0.510
7 days	20	268.000	260.000	13.4000	0.510

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
57	-0.51031	0.6098

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.2963	1	0.5862

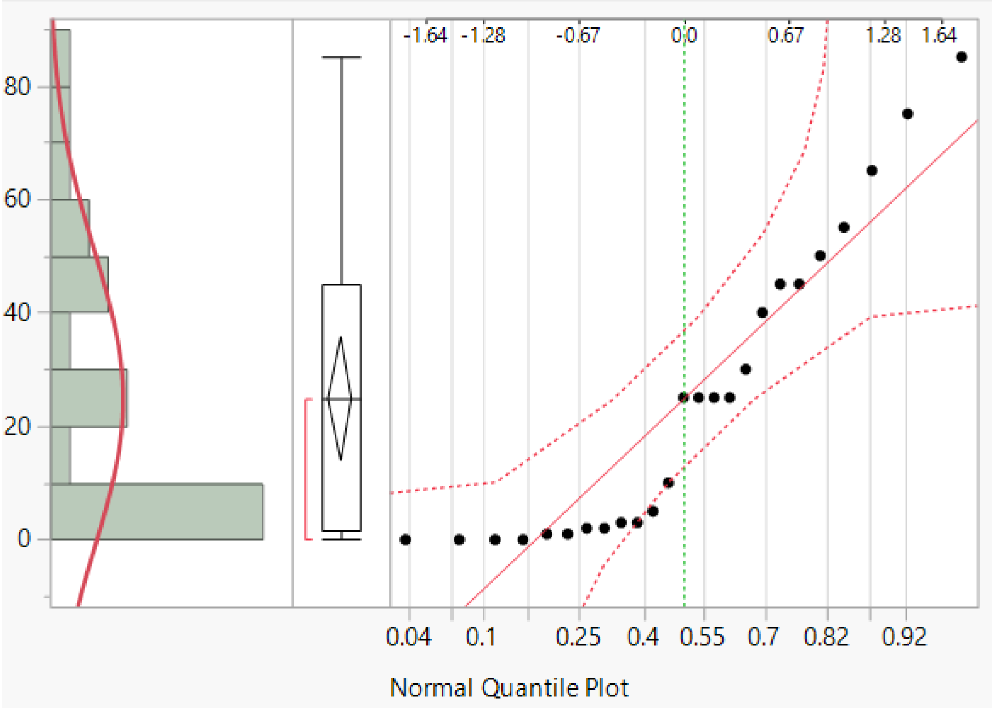
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	1.875000	3.674235	0.5103104	0.6098	2.000000	-6.00000	13.00000

5 psi – 48 Hours:7+ Days – SBCA – Wood Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.856567	0.0024*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.7658	1	23	0.1099
Brown-Forsythe	4.4322	1	23	0.0464*
Levene	4.9452	1	23	0.0363*
Bartlett	3.3812	1	.	0.0659
F Test 2-sided	6.2025	19	4	0.0892

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	34.000	65.000	6.8000	-2.082
7 days	20	291.000	260.000	14.5500	2.082

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
34	-2.08170	0.0374*

1-Way Test, ChiSquare Approximation

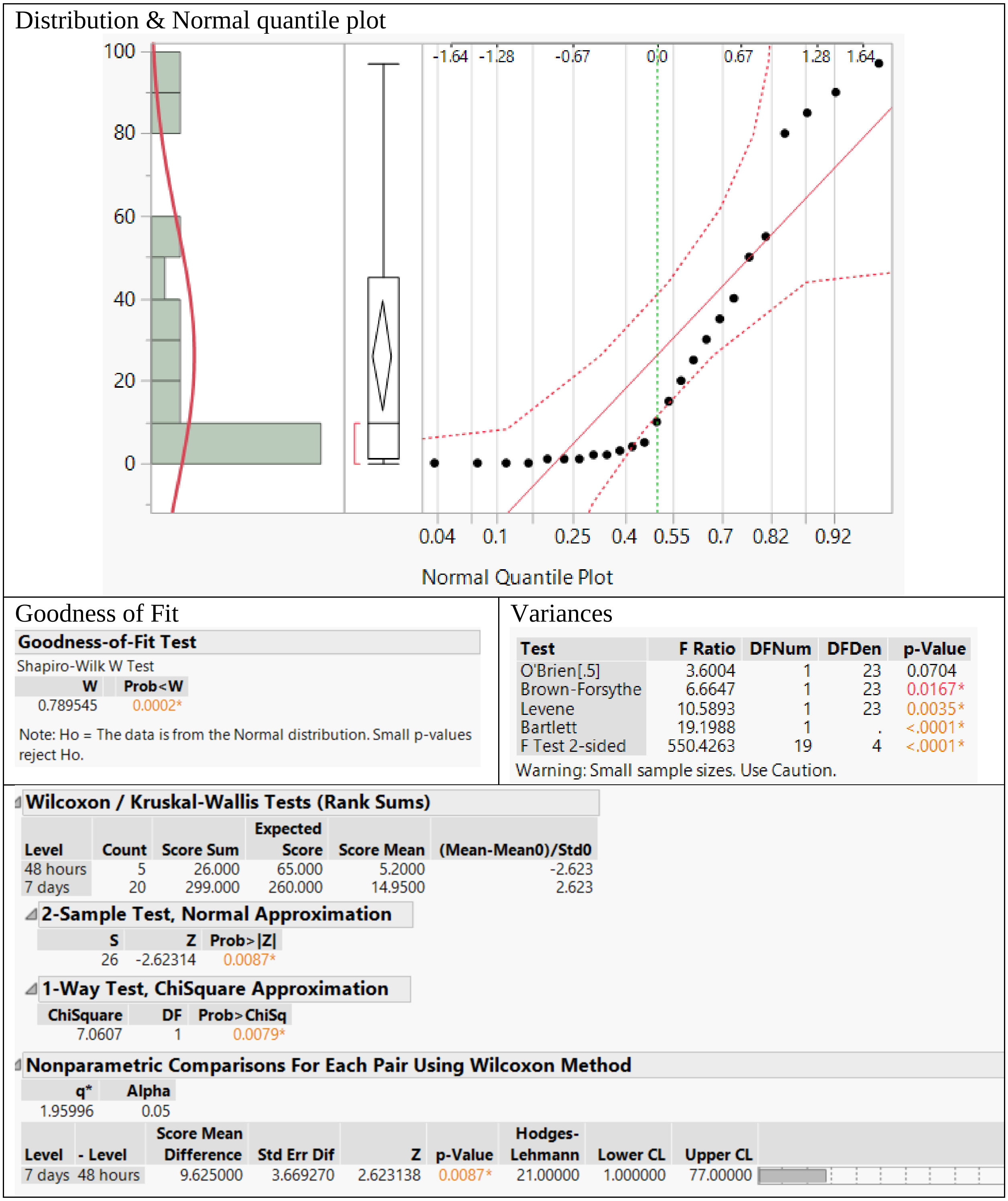
ChiSquare	DF	Prob>ChiSq
4.4767	1	0.0344*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	7.625000	3.662877	2.081697	0.0374*	20.00000	0	50.00000

25 psi – 48 Hours:7+ Days – SBCA – Wood Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.789545	0.0002*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	3.6004	1	23	0.0704
Brown-Forsythe	6.6647	1	23	0.0167*
Levene	10.5893	1	23	0.0035*
Bartlett	19.1988	1	.	<.0001*
F Test 2-sided	550.4263	19	4	<.0001*

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	26.000	65.000	5.2000	-2.623
7 days	20	299.000	260.000	14.9500	2.623

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
26	-2.62314	0.0087*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
7.0607	1	0.0079*

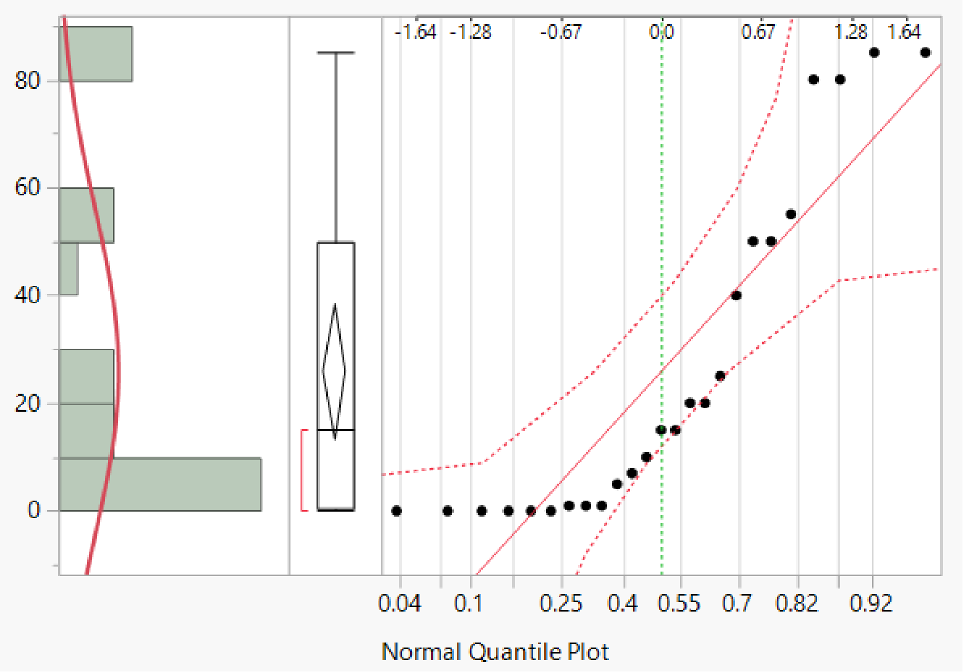
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

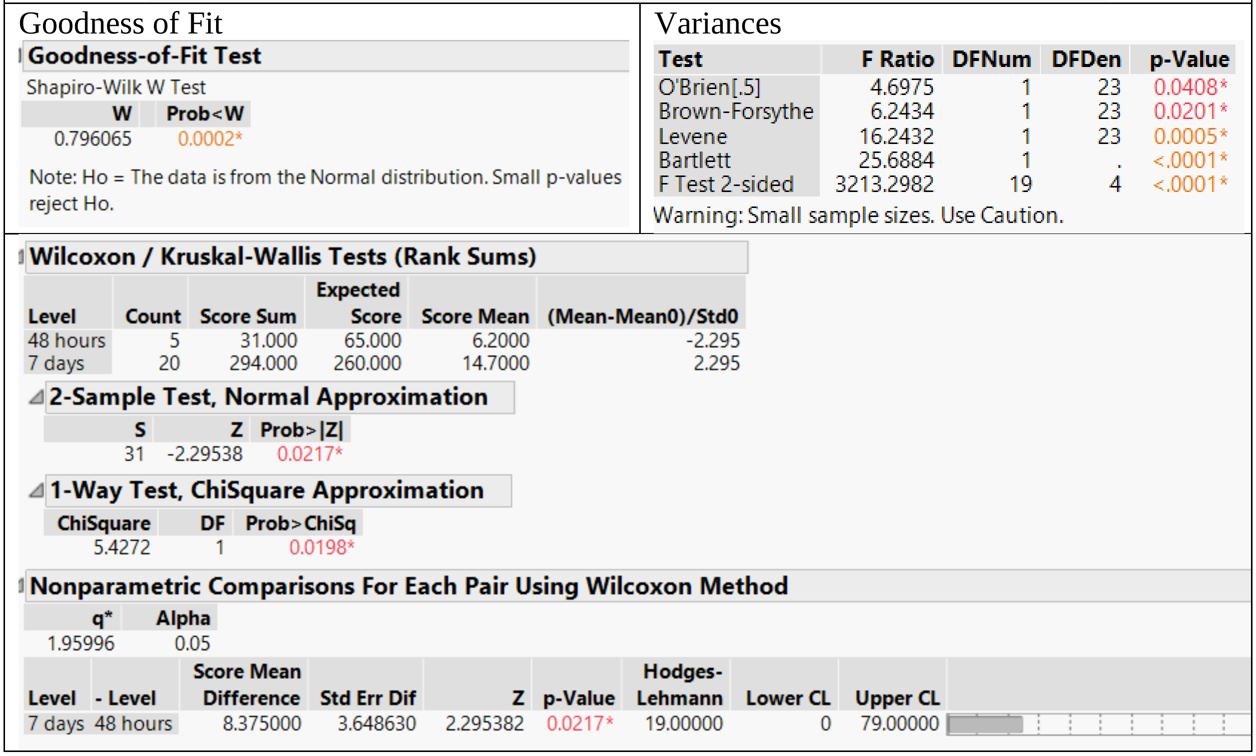
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	9.625000	3.669270	2.623138	0.0087*	21.00000	1.000000	77.00000

50 psi – 48 Hours:7+ Days – SBCA – Wood Failure

Distribution & Normal quantile plot





Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.796065	0.0002*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	4.6975	1	23	0.0408*
Brown-Forsythe	6.2434	1	23	0.0201*
Levene	16.2432	1	23	0.0005*
Bartlett	25.6884	1	.	<.0001*
F Test 2-sided	3213.2982	19	4	<.0001*

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	31.000	65.000	6.2000	-2.295
7 days	20	294.000	260.000	14.7000	2.295

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
31	-2.29538	0.0217*

1-Way Test, ChiSquare Approximation

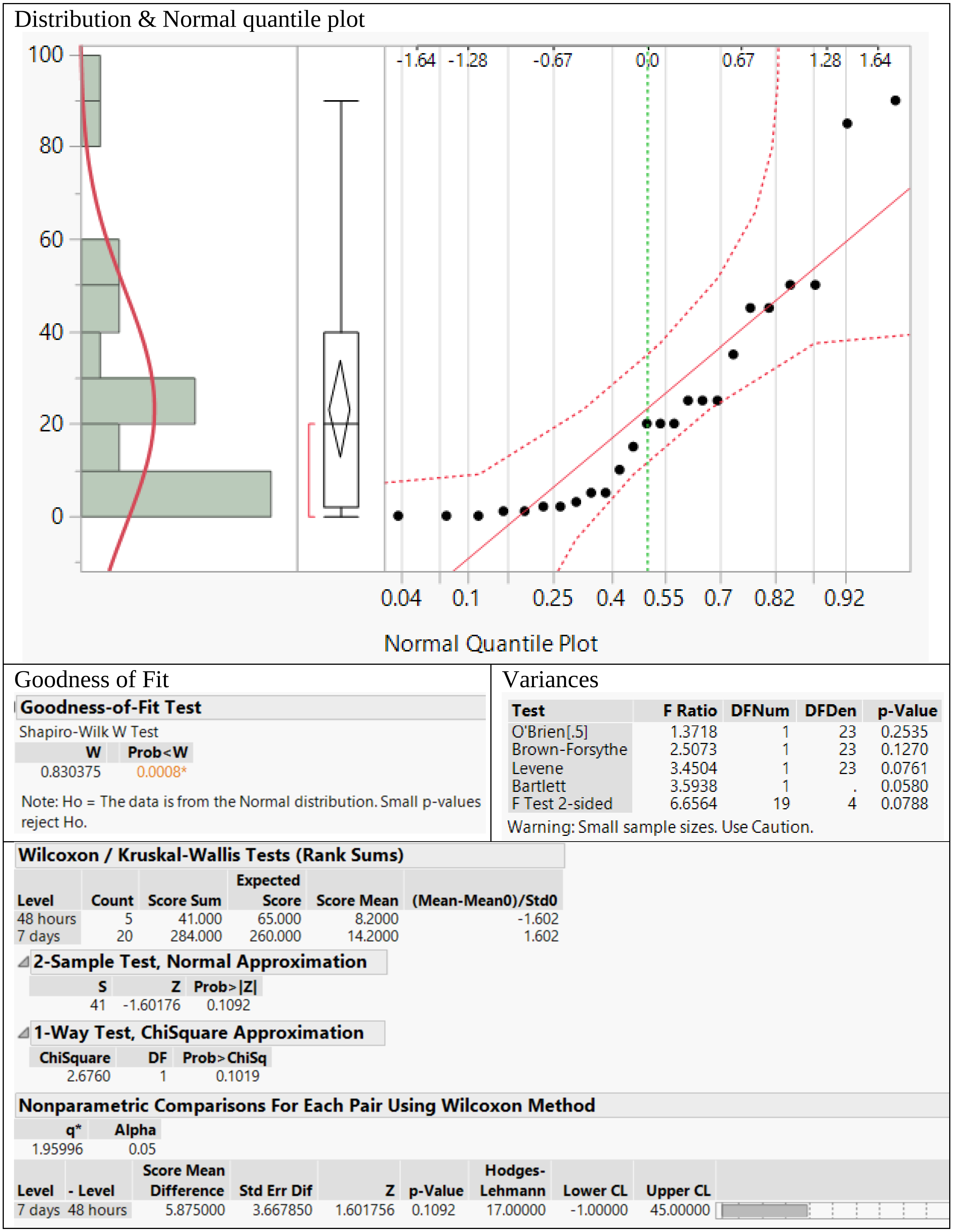
ChiSquare	DF	Prob>ChiSq
5.4272	1	0.0198*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	8.375000	3.648630	2.295382	0.0217*	19.00000	0	79.00000

75 psi – 48 Hours:7+ Days – SBCA – Wood Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.830375	0.0008*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	1.3718	1	23	0.2535
Brown-Forsythe	2.5073	1	23	0.1270
Levene	3.4504	1	23	0.0761
Bartlett	3.5938	1	.	0.0580
F Test 2-sided	6.6564	19	4	0.0788

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	41.000	65.000	8.2000	-1.602
7 days	20	284.000	260.000	14.2000	1.602

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
41	-1.60176	0.1092

1-Way Test, ChiSquare Approximation

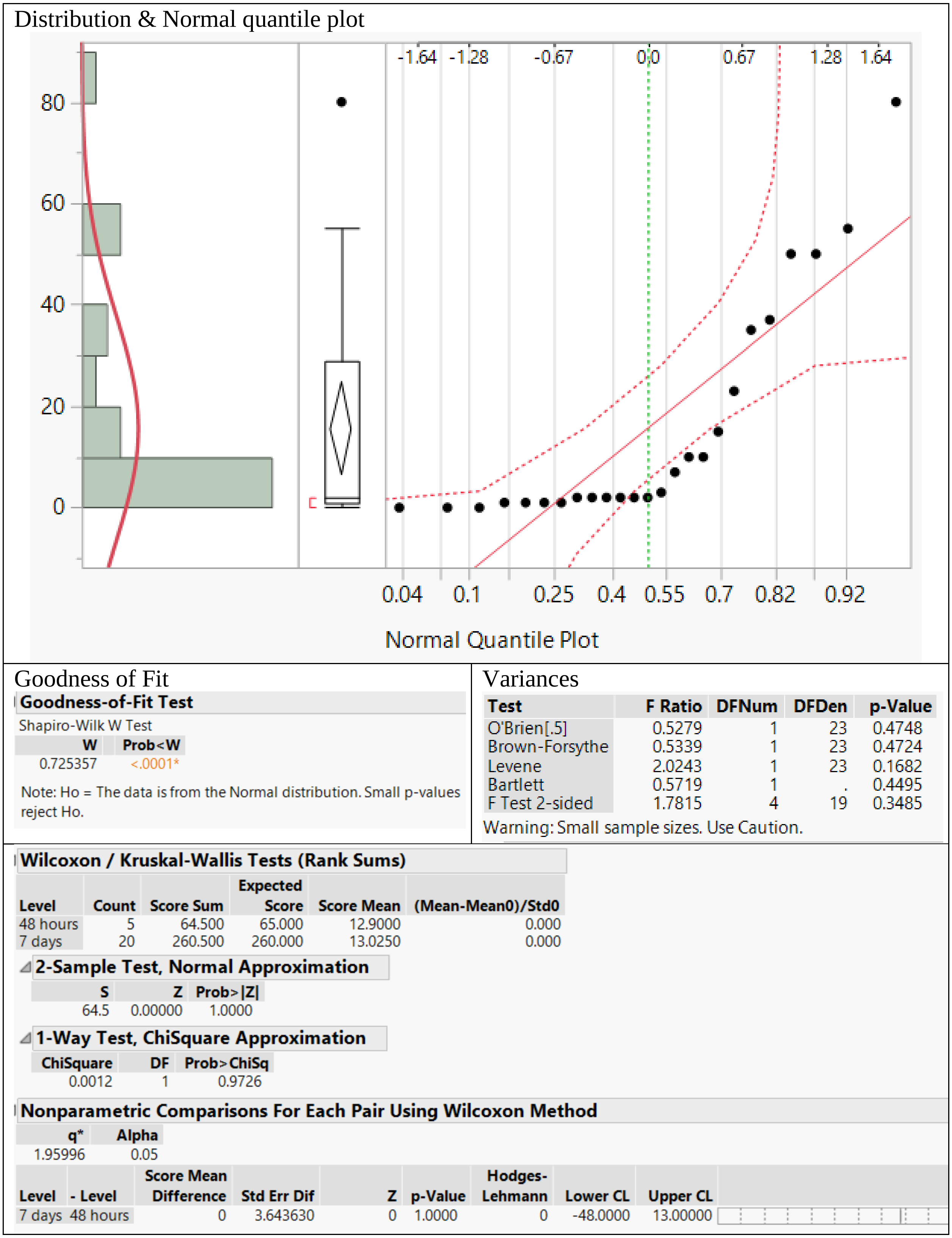
ChiSquare	DF	Prob>ChiSq
2.6760	1	0.1019

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	5.875000	3.667850	1.601756	0.1092	17.00000	-1.00000	45.00000

100 psi – 48 Hours:7+ Days – SBCA – Wood Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.725357	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.5279	1	23	0.4748
Brown-Forsythe	0.5339	1	23	0.4724
Levene	2.0243	1	23	0.1682
Bartlett	0.5719	1	.	0.4495
F Test 2-sided	1.7815	4	19	0.3485

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
48 hours	5	64.500	65.000	12.9000	0.000
7 days	20	260.500	260.000	13.0250	0.000

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
64.5	0.00000	1.0000

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.0012	1	0.9726

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

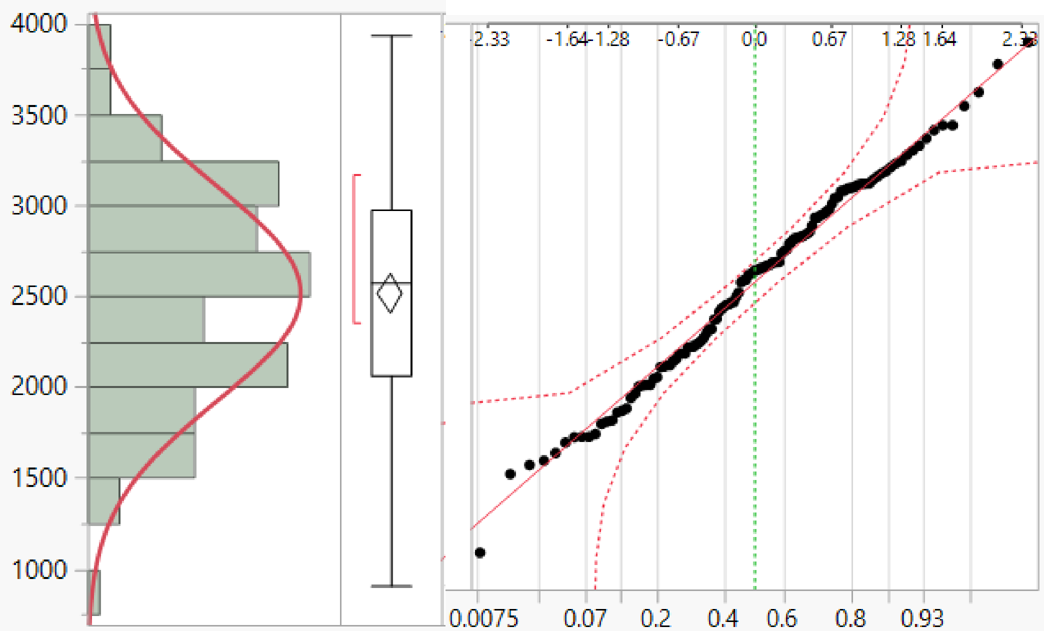
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
7 days	48 hours	0	3.643630	0	1.0000	0	-48.0000	13.00000

5.2 Appendix B – Statistics for the effect of pre-compression pressure on the tensile strength perpendicular to the grain of the connection

7+ Days – SBCA – Load at Failure

Distribution & Normal quantile plot

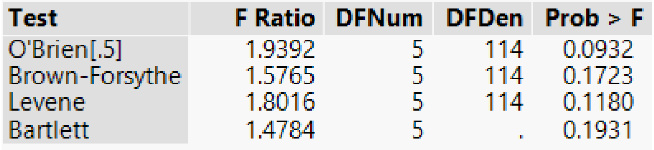


Goodness of Fit

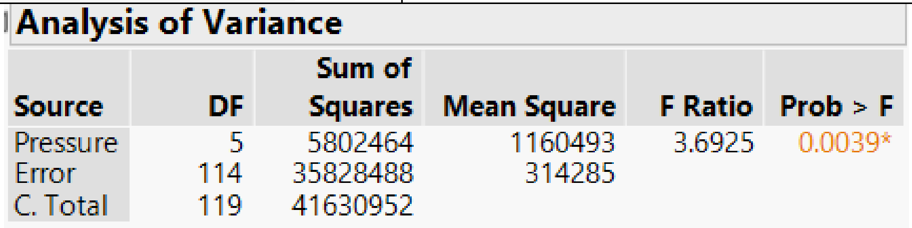
Shapiro-Wilk W Test

W	Prob<W
0.991268	0.6517

Variances

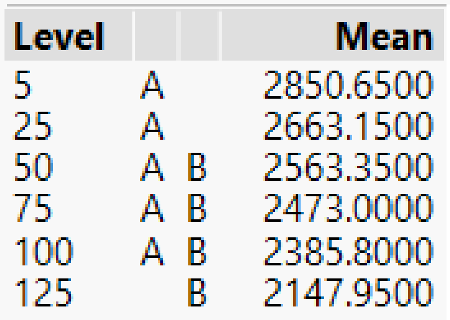


Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.9392	5	114	0.0932
Brown-Forsythe	1.5765	5	114	0.1723
Levene	1.8016	5	114	0.1180
Bartlett	1.4784	5	.	0.1931



Analysis of Variance

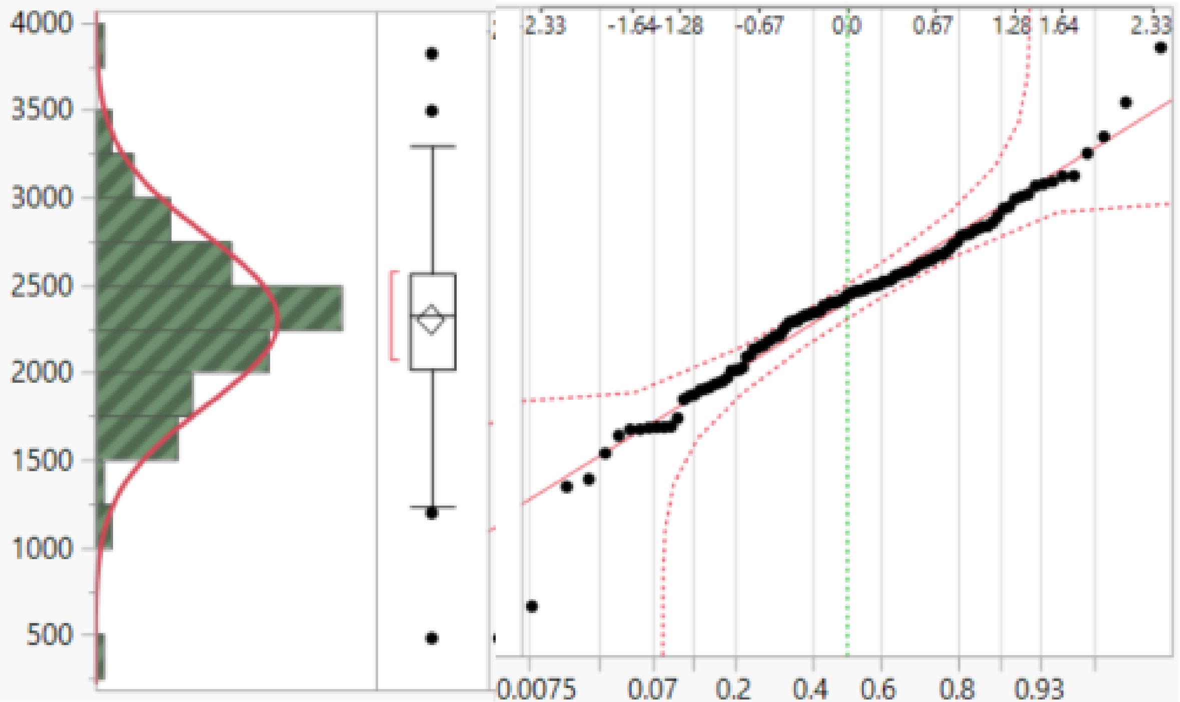
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure	5	5802464	1160493	3.6925	0.0039*
Error	114	35828488	314285		
C. Total	119	41630952			



Level			Mean
5	A		2850.6500
25	A		2663.1500
50	A	B	2563.3500
75	A	B	2473.0000
100	A	B	2385.8000
125		B	2147.9500

7+ Days – EPI – Load at Failure

Distribution & Normal quantile plot

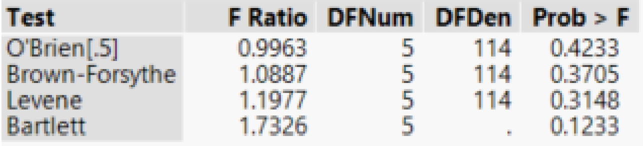


Goodness of Fit

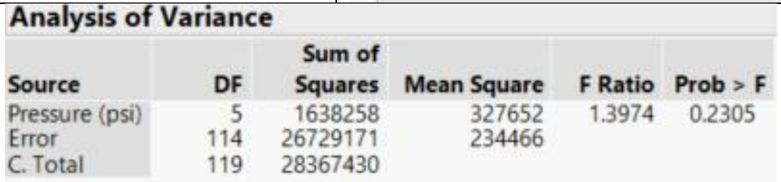
Shapiro-Wilk W Test

W	Prob<W
0.981366	0.0954

Variances

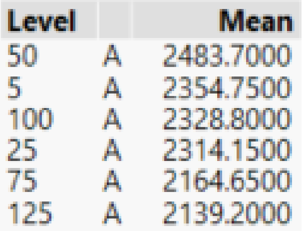


Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.9963	5	114	0.4233
Brown-Forsythe	1.0887	5	114	0.3705
Levene	1.1977	5	114	0.3148
Bartlett	1.7326	5	.	0.1233



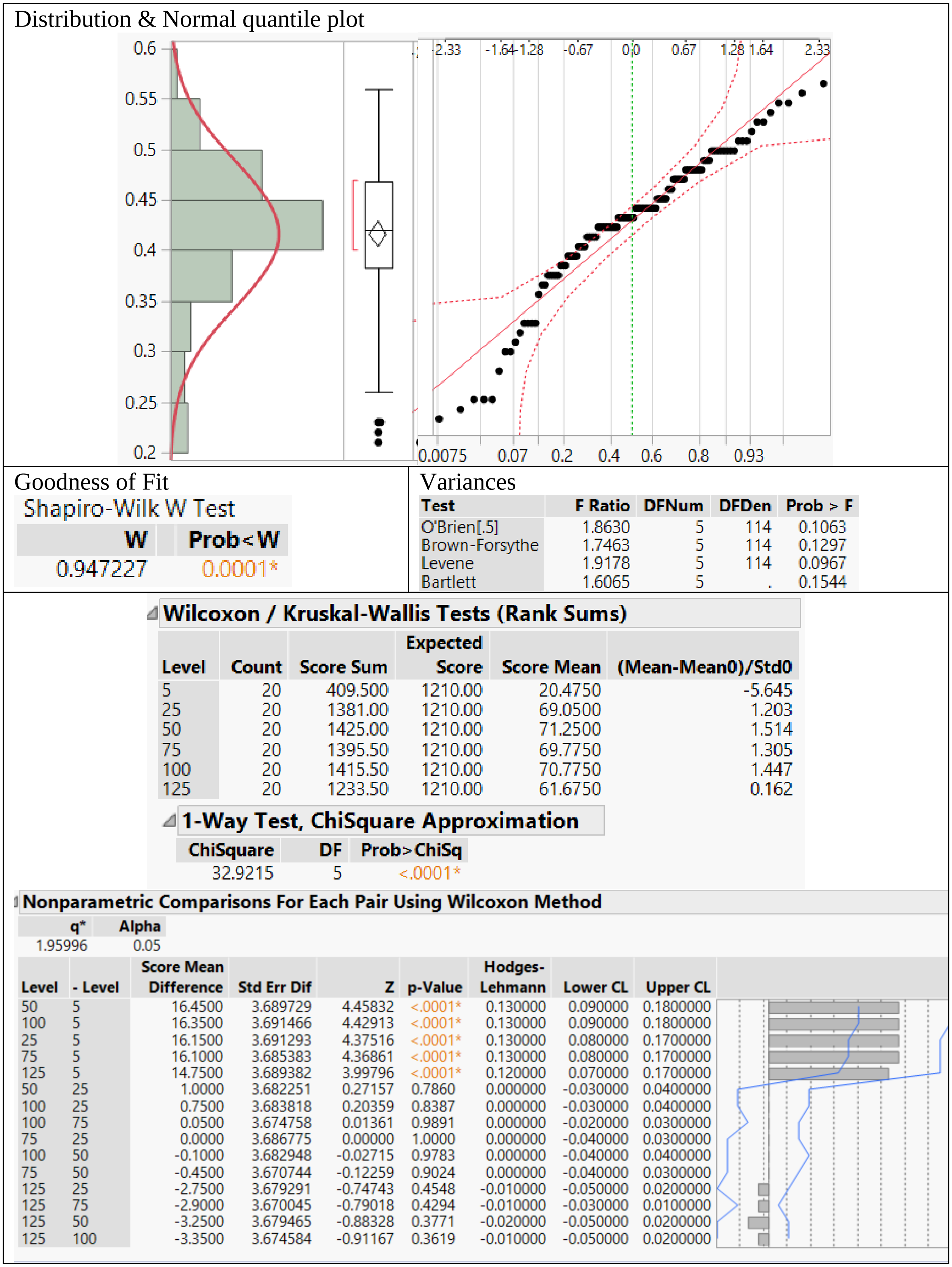
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure (psi)	5	1638258	327652	1.3974	0.2305
Error	114	26729171	234466		
C. Total	119	28367430			



Level		Mean
50	A	2483.7000
5	A	2354.7500
100	A	2328.8000
25	A	2314.1500
75	A	2164.6500
125	A	2139.2000

7+ Days – SBCA – Deformation at Failure



Distribution & Normal quantile plot

Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.947227	0.0001*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.8630	5	114	0.1063
Brown-Forsythe	1.7463	5	114	0.1297
Levene	1.9178	5	114	0.0967
Bartlett	1.6065	5	.	0.1544

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
5	20	409.500	1210.00	20.4750	-5.645
25	20	1381.00	1210.00	69.0500	1.203
50	20	1425.00	1210.00	71.2500	1.514
75	20	1395.50	1210.00	69.7750	1.305
100	20	1415.50	1210.00	70.7750	1.447
125	20	1233.50	1210.00	61.6750	0.162

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
32.9215	5	<.0001*

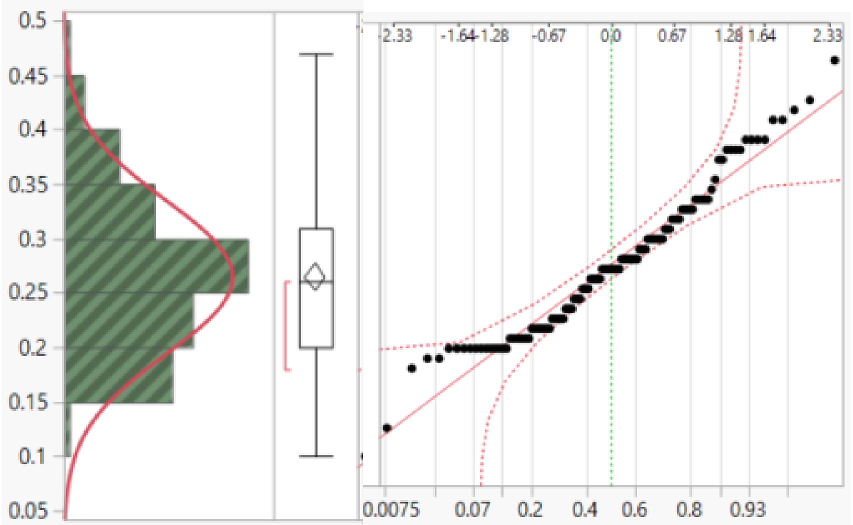
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	5	16.4500	3.689729	4.45832	<.0001*	0.130000	0.090000	0.1800000
100	5	16.3500	3.691466	4.42913	<.0001*	0.130000	0.090000	0.1800000
25	5	16.1500	3.691293	4.37516	<.0001*	0.130000	0.080000	0.1700000
75	5	16.1000	3.685383	4.36861	<.0001*	0.130000	0.080000	0.1700000
125	5	14.7500	3.689382	3.99796	<.0001*	0.120000	0.070000	0.1700000
50	25	1.0000	3.682251	0.27157	0.7860	0.000000	-0.030000	0.0400000
100	25	0.7500	3.683818	0.20359	0.8387	0.000000	-0.030000	0.0400000
100	75	0.0500	3.674758	0.01361	0.9891	0.000000	-0.020000	0.0300000
75	25	0.0000	3.686775	0.00000	1.0000	0.000000	-0.040000	0.0300000
100	50	-0.1000	3.682948	-0.02715	0.9783	0.000000	-0.040000	0.0400000
75	50	-0.4500	3.670744	-0.12259	0.9024	0.000000	-0.040000	0.0300000
125	25	-2.7500	3.679291	-0.74743	0.4548	-0.010000	-0.050000	0.0200000
125	75	-2.9000	3.670045	-0.79018	0.4294	-0.010000	-0.030000	0.0100000
125	50	-3.2500	3.679465	-0.88328	0.3771	-0.020000	-0.050000	0.0200000
125	100	-3.3500	3.674584	-0.91167	0.3619	-0.010000	-0.050000	0.0200000

7+ Days – EPI – Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.960064	0.0013*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.0404	5	114	0.0782
Brown-Forsythe	2.1360	5	114	0.0661
Levene	2.8134	5	114	0.0196*
Bartlett	3.4789	5	.	0.0038*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
5	20	552.500	1210.00	27.6250	-4.634
25	20	727.000	1210.00	36.3500	-3.403
50	20	1797.00	1210.00	89.8500	4.137
75	20	1405.50	1210.00	70.2750	1.375
100	20	1302.50	1210.00	65.1250	0.649
125	20	1475.50	1210.00	73.7750	1.869

1-Way Test, ChiSquare Approximation

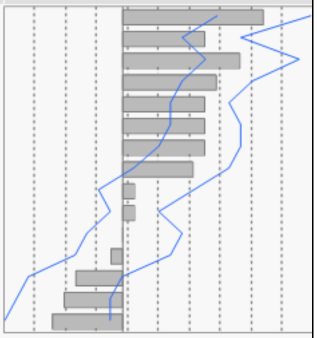
ChiSquare	DF	Prob>ChiSq
46.7475	5	<.0001*

Level					Mean
50	A				0.32900000
125	A	B			0.28900000
75		B			0.27400000
100		B	C		0.27050000
25			C	D	0.22000000
5				D	0.20350000

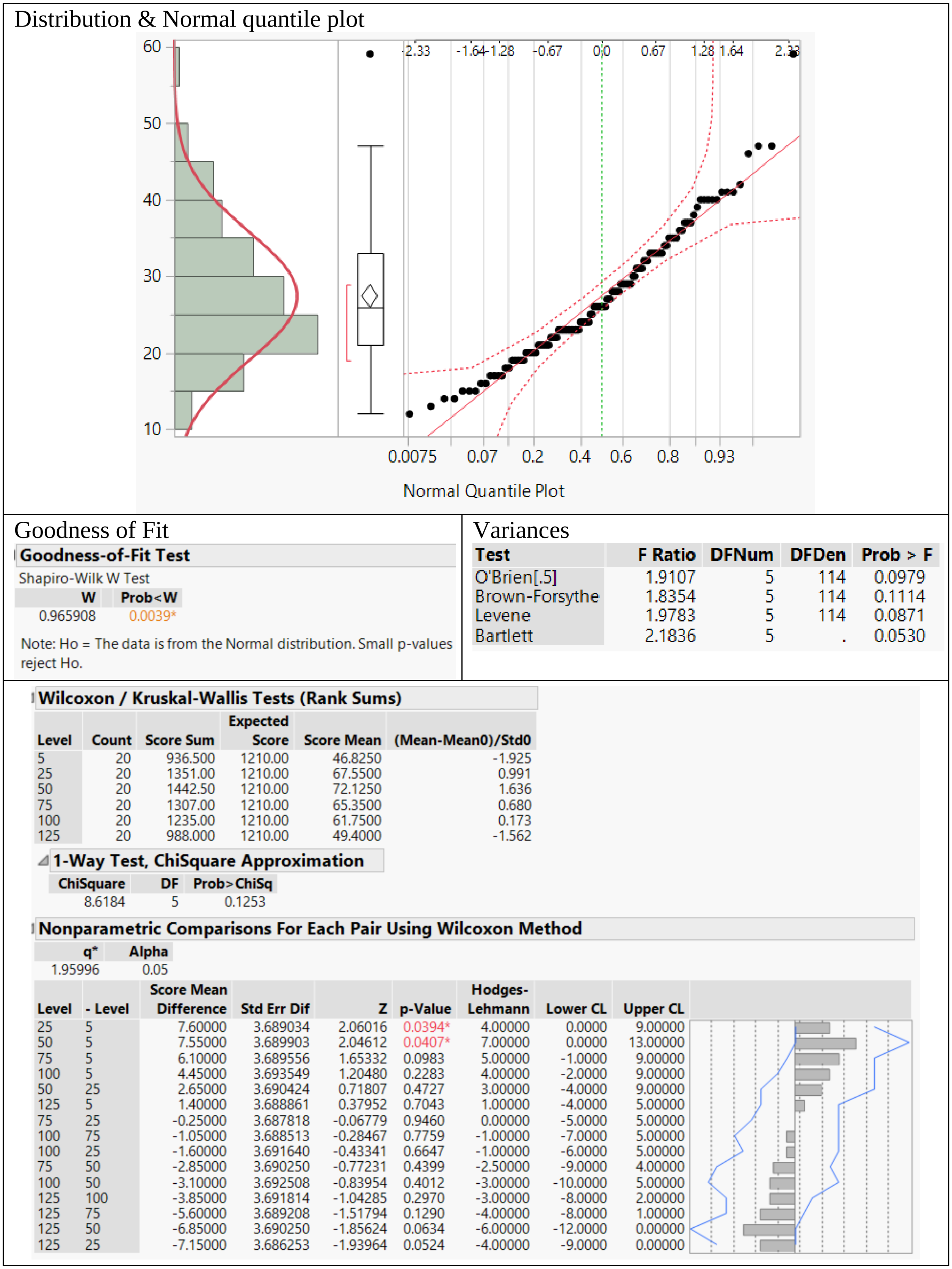
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	5	18.9500	3.688513	5.13757	<.0001*	0.120000	0.080000	0.160000
125	5	16.7500	3.682948	4.54799	<.0001*	0.070000	0.050000	0.100000
50	25	16.2500	3.687470	4.40682	<.0001*	0.100000	0.070000	0.150000
75	5	14.9000	3.679116	4.04989	<.0001*	0.080000	0.050000	0.110000
125	25	13.6000	3.682773	3.69287	0.0002*	0.070000	0.040000	0.090000
100	5	12.5500	3.680162	3.41018	0.0006*	0.070000	0.040000	0.100000
75	25	11.3500	3.682599	3.08206	0.0021*	0.070000	0.030000	0.100000
100	25	9.3000	3.682948	2.52515	0.0116*	0.060000	0.010000	0.090000
125	100	2.5500	3.682077	0.69254	0.4886	0.010000	-0.020000	0.060000
25	5	2.3500	3.663927	0.64139	0.5213	0.010000	-0.010000	0.030000
125	75	0.2500	3.681032	0.06792	0.9459	0.000000	-0.030000	0.050000
100	75	-1.6500	3.683296	-0.44797	0.6542	-0.010000	-0.040000	0.040000
125	50	-6.7500	3.686949	-1.83078	0.0671	-0.040000	-0.080000	0.000000
75	50	-8.1500	3.689382	-2.20904	0.0272*	-0.050000	-0.090000	-0.010000
100	50	-8.3500	3.689382	-2.26325	0.0236*	-0.060000	-0.100000	-0.010000



7+ Days – SBCA – Energy



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.965908	0.0039*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.9107	5	114	0.0979
Brown-Forsythe	1.8354	5	114	0.1114
Levene	1.9783	5	114	0.0871
Bartlett	2.1836	5	.	0.0530

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
5	20	936.500	1210.00	46.8250	-1.925
25	20	1351.00	1210.00	67.5500	0.991
50	20	1442.50	1210.00	72.1250	1.636
75	20	1307.00	1210.00	65.3500	0.680
100	20	1235.00	1210.00	61.7500	0.173
125	20	988.000	1210.00	49.4000	-1.562

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
8.6184	5	0.1253

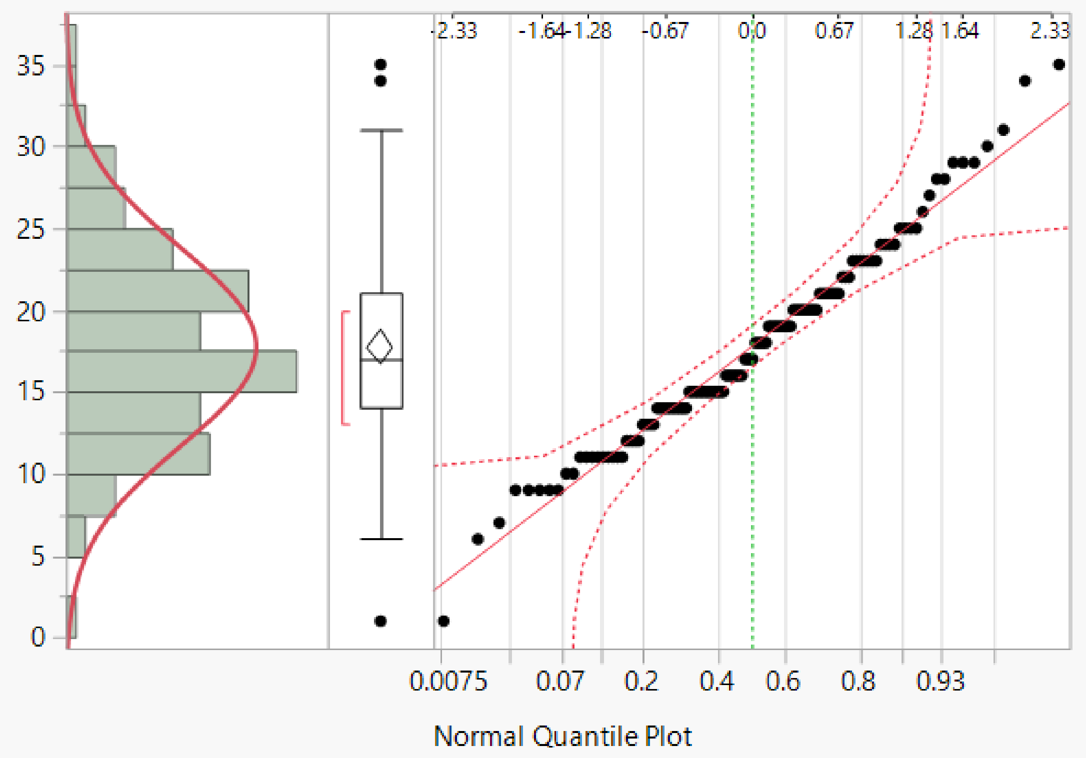
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

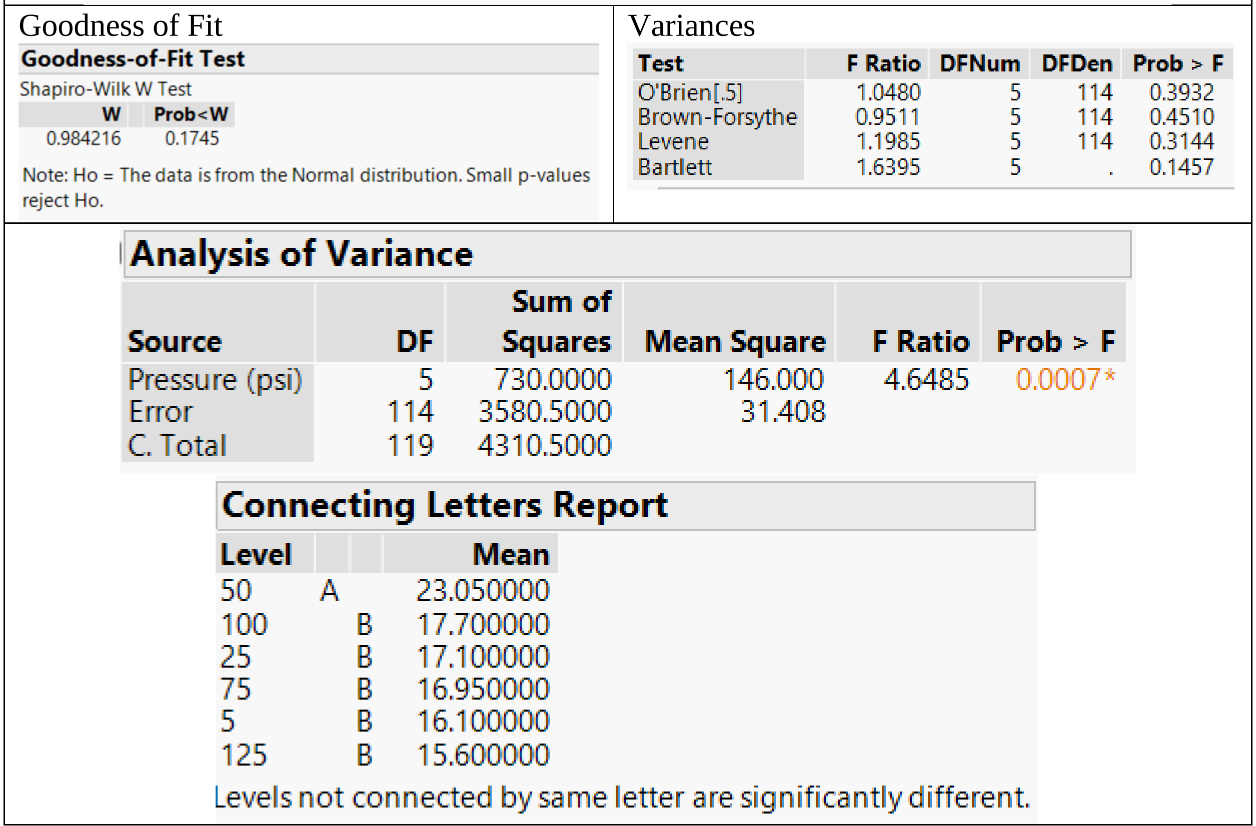
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
25	5	7.60000	3.689034	2.06016	0.0394*	4.00000	0.0000	9.00000
50	5	7.55000	3.689903	2.04612	0.0407*	7.00000	0.0000	13.00000
75	5	6.10000	3.689556	1.65332	0.0983	5.00000	-1.0000	9.00000
100	5	4.45000	3.693549	1.20480	0.2283	4.00000	-2.0000	9.00000
50	25	2.65000	3.690424	0.71807	0.4727	3.00000	-4.0000	9.00000
125	5	1.40000	3.688861	0.37952	0.7043	1.00000	-4.0000	5.00000
75	25	-0.25000	3.687818	-0.06779	0.9460	0.00000	-5.0000	5.00000
100	75	-1.05000	3.688513	-0.28467	0.7759	-1.00000	-7.0000	5.00000
100	25	-1.60000	3.691640	-0.43341	0.6647	-1.00000	-6.0000	5.00000
75	50	-2.85000	3.690250	-0.77231	0.4399	-2.50000	-9.0000	4.00000
100	50	-3.10000	3.692508	-0.83954	0.4012	-3.00000	-10.0000	5.00000
125	100	-3.85000	3.691814	-1.04285	0.2970	-3.00000	-8.0000	2.00000
125	75	-5.60000	3.689208	-1.51794	0.1290	-4.00000	-8.0000	1.00000
125	50	-6.85000	3.690250	-1.85624	0.0634	-6.00000	-12.0000	0.00000
125	25	-7.15000	3.686253	-1.93964	0.0524	-4.00000	-9.0000	0.00000

7+ Days – EPI – Energy

Distribution & Normal quantile plot





Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.984216	0.1745

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.0480	5	114	0.3932
Brown-Forsythe	0.9511	5	114	0.4510
Levene	1.1985	5	114	0.3144
Bartlett	1.6395	5	.	0.1457

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure (psi)	5	730.0000	146.000	4.6485	0.0007*
Error	114	3580.5000	31.408		
C. Total	119	4310.5000			

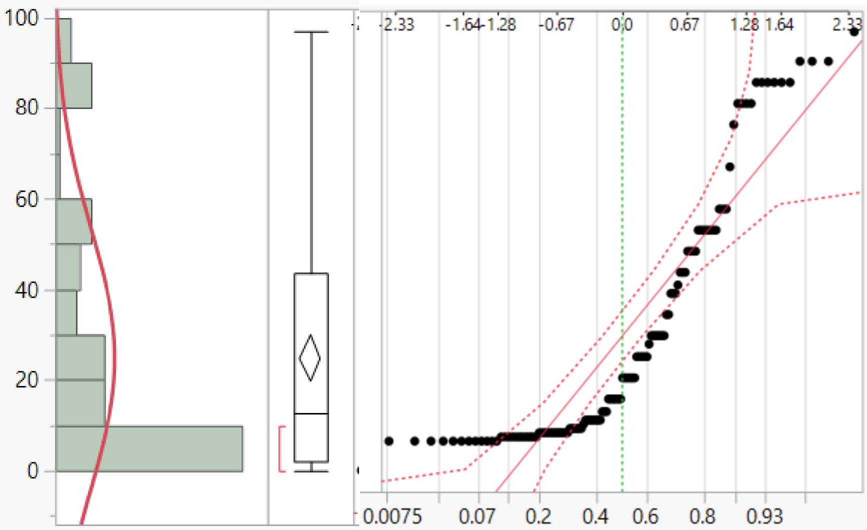
Connecting Letters Report

Level			Mean
50	A		23.050000
100		B	17.700000
25		B	17.100000
75		B	16.950000
5		B	16.100000
125		B	15.600000

Levels not connected by same letter are significantly different.

7+ Days – SBCA –Wood Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.807653	<.0001*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.7161	5	114	0.6126
Brown-Forsythe	1.8471	5	114	0.1092
Levene	2.1304	5	114	0.0668
Bartlett	0.8799	5	.	0.4934

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
5	20	1341.00	1210.00	67.0500	0.921
25	20	1365.50	1210.00	68.2750	1.094
50	20	1360.50	1210.00	68.0250	1.059
75	20	1322.50	1210.00	66.1250	0.790
100	20	935.500	1210.00	46.7750	-1.934
125	20	935.000	1210.00	46.7500	-1.937

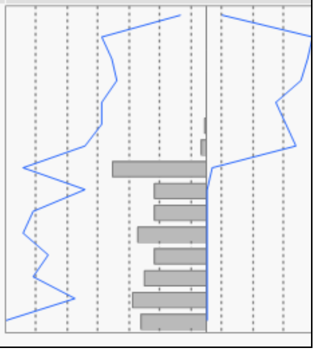
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
9.4468	5	0.0925

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

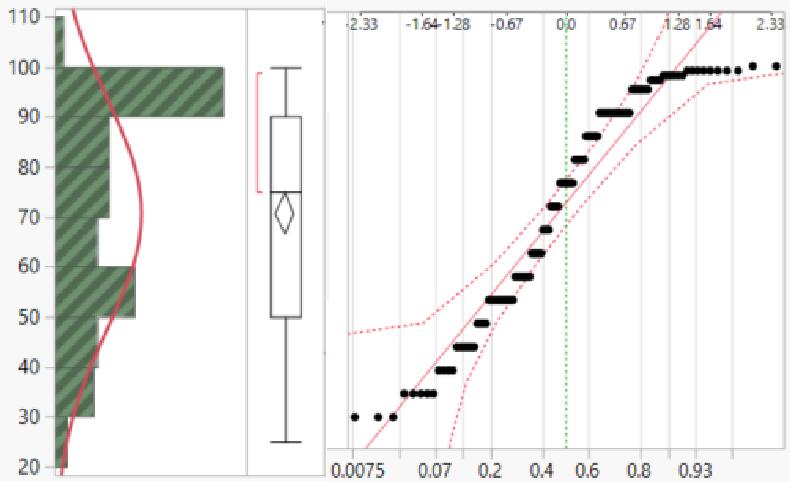
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
125	100	0.55000	3.675804	0.14963	0.8811	0.0000	-5.0000	3.00000
25	5	0.45000	3.689382	0.12197	0.9029	0.0000	-20.0000	20.00000
50	5	0.35000	3.688513	0.09489	0.9244	0.0000	-18.0000	19.00000
50	25	-0.40000	3.688339	-0.10845	0.9136	0.0000	-17.0000	18.00000
75	50	-0.65000	3.682599	-0.17651	0.8599	0.0000	-20.0000	13.00000
75	25	-0.95000	3.689382	-0.25750	0.7968	-0.5000	-20.0000	15.00000
75	5	-1.15000	3.686601	-0.31194	0.7551	-1.0000	-23.0000	17.00000
125	5	-5.90000	3.684340	-1.60137	0.1093	-18.0000	-35.0000	1.00000
100	75	-6.50000	3.680858	-1.76589	0.0774	-10.0000	-23.0000	0.00000
100	25	-6.65000	3.682599	-1.80579	0.0710	-10.0000	-33.0000	0.00000
100	50	-6.70000	3.683296	-1.81902	0.0689	-13.0000	-35.0000	0.00000
100	5	-6.80000	3.681032	-1.84731	0.0647	-10.0000	-30.0000	0.00000
125	25	-6.85000	3.686079	-1.85834	0.0631	-12.0000	-33.0000	0.00000
125	75	-7.55000	3.685557	-2.04854	0.0405*	-14.0000	-25.0000	0.00000
125	50	-7.60000	3.682425	-2.06386	0.0390*	-12.5000	-38.0000	0.00000



7+ Days – EPI –Wood Failure

Distribution & Normal quantile plot

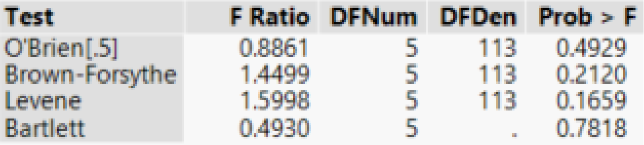


Goodness of Fit

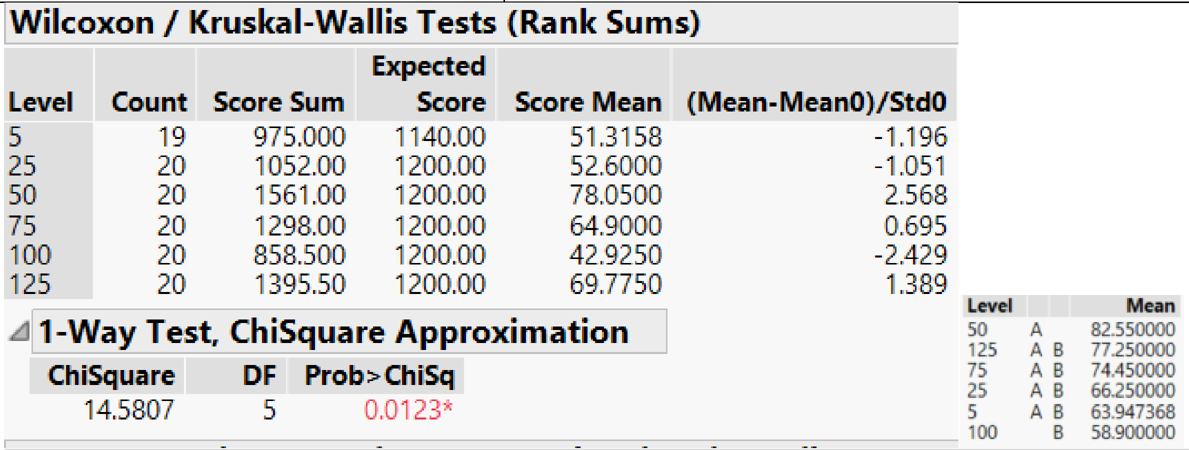
Shapiro-Wilk W Test

W	Prob<W
0.914436	<.0001*

Variances



Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.8861	5	113	0.4929
Brown-Forsythe	1.4499	5	113	0.2120
Levene	1.5998	5	113	0.1659
Bartlett	0.4930	5	.	0.7818



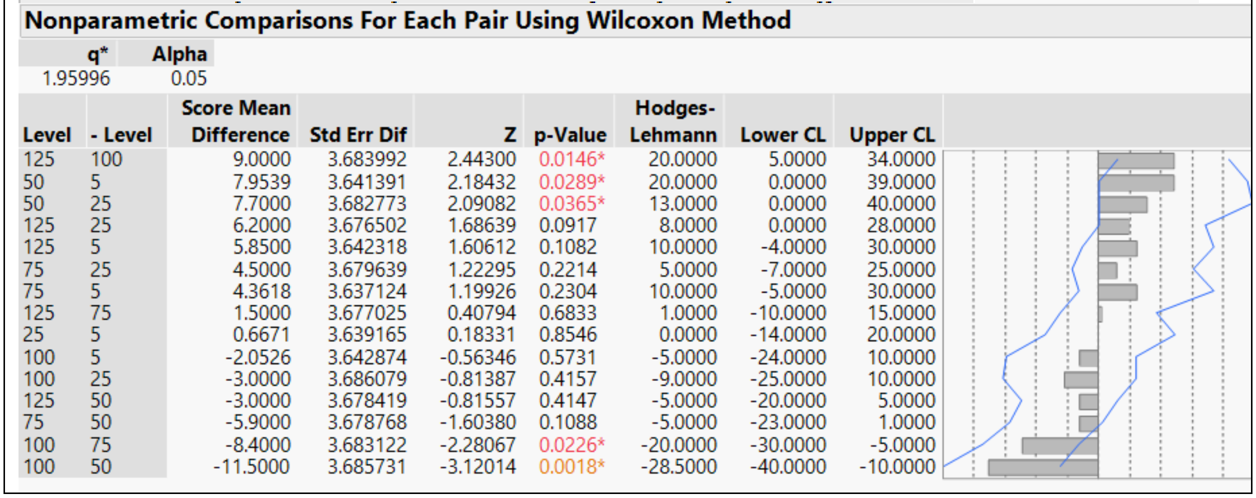
Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
5	19	975.000	1140.00	51.3158	-1.196
25	20	1052.00	1200.00	52.6000	-1.051
50	20	1561.00	1200.00	78.0500	2.568
75	20	1298.00	1200.00	64.9000	0.695
100	20	858.500	1200.00	42.9250	-2.429
125	20	1395.50	1200.00	69.7750	1.389

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
14.5807	5	0.0123*

Level			Mean
50	A		82.550000
125	A	B	77.250000
75	A	B	74.450000
25	A	B	66.250000
5	A	B	63.947368
100		B	58.900000



Nonparametric Comparisons For Each Pair Using Wilcoxon Method

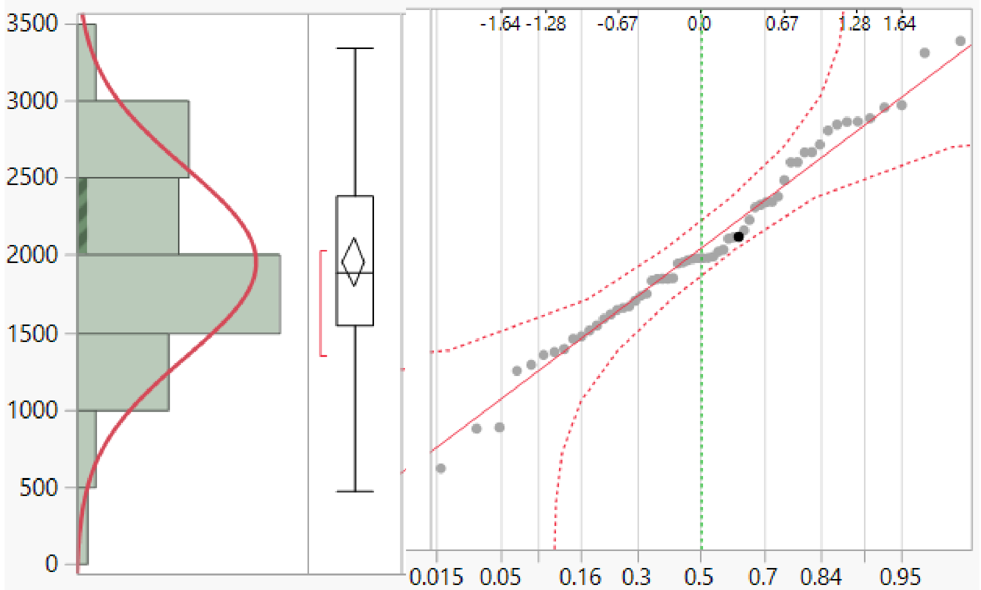
q*	Alpha
1.95996	0.05

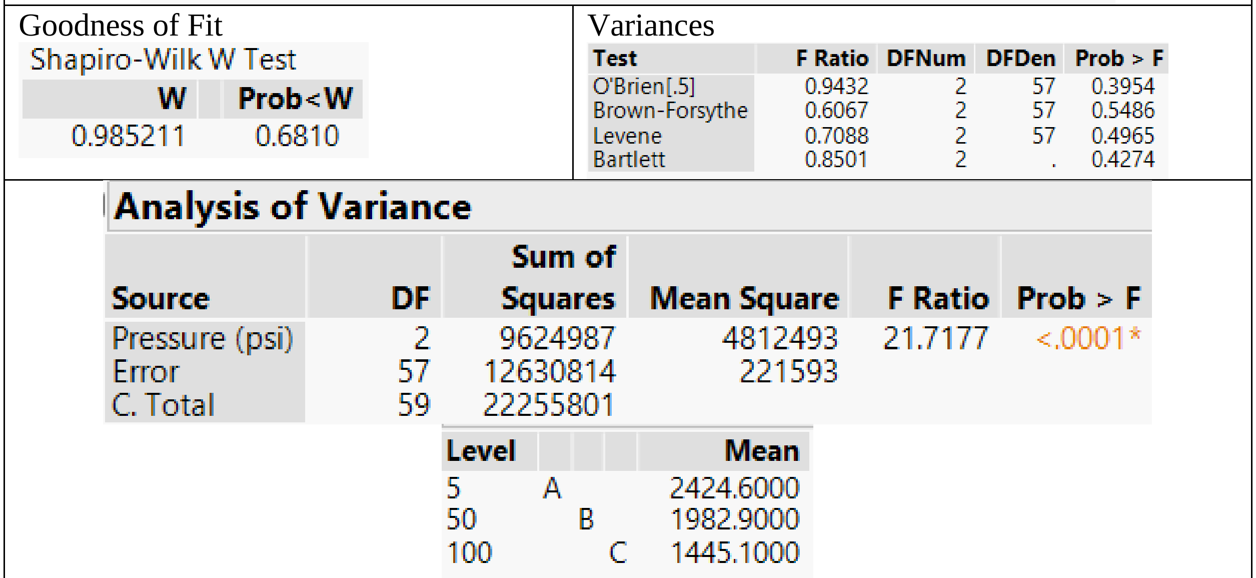
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
125	100	9.0000	3.683992	2.44300	0.0146*	20.0000	5.0000	34.0000
50	5	7.9539	3.641391	2.18432	0.0289*	20.0000	0.0000	39.0000
50	25	7.7000	3.682773	2.09082	0.0365*	13.0000	0.0000	40.0000
125	25	6.2000	3.676502	1.68639	0.0917	8.0000	0.0000	28.0000
125	5	5.8500	3.642318	1.60612	0.1082	10.0000	-4.0000	30.0000
75	25	4.5000	3.679639	1.22295	0.2214	5.0000	-7.0000	25.0000
75	5	4.3618	3.637124	1.19926	0.2304	10.0000	-5.0000	30.0000
125	75	1.5000	3.677025	0.40794	0.6833	1.0000	-10.0000	15.0000
25	5	0.6671	3.639165	0.18331	0.8546	0.0000	-14.0000	20.0000
100	5	-2.0526	3.642874	-0.56346	0.5731	-5.0000	-24.0000	10.0000
100	25	-3.0000	3.686079	-0.81387	0.4157	-9.0000	-25.0000	10.0000
125	50	-3.0000	3.678419	-0.81557	0.4147	-5.0000	-20.0000	5.0000
75	50	-5.9000	3.678768	-1.60380	0.1088	-5.0000	-23.0000	1.0000
100	75	-8.4000	3.683122	-2.28067	0.0226*	-20.0000	-30.0000	-5.0000
100	50	-11.5000	3.685731	-3.12014	0.0018*	-28.5000	-40.0000	-10.0000

5.3 Appendix C – Statistics for the effect of pre-compression pressure on the tensile strength parallel to the grain of the connection

7+ Days – SBCA – Load at Failure

Distribution & Normal quantile plot





Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.985211	0.6810

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.9432	2	57	0.3954
Brown-Forsythe	0.6067	2	57	0.5486
Levene	0.7088	2	57	0.4965
Bartlett	0.8501	2	.	0.4274

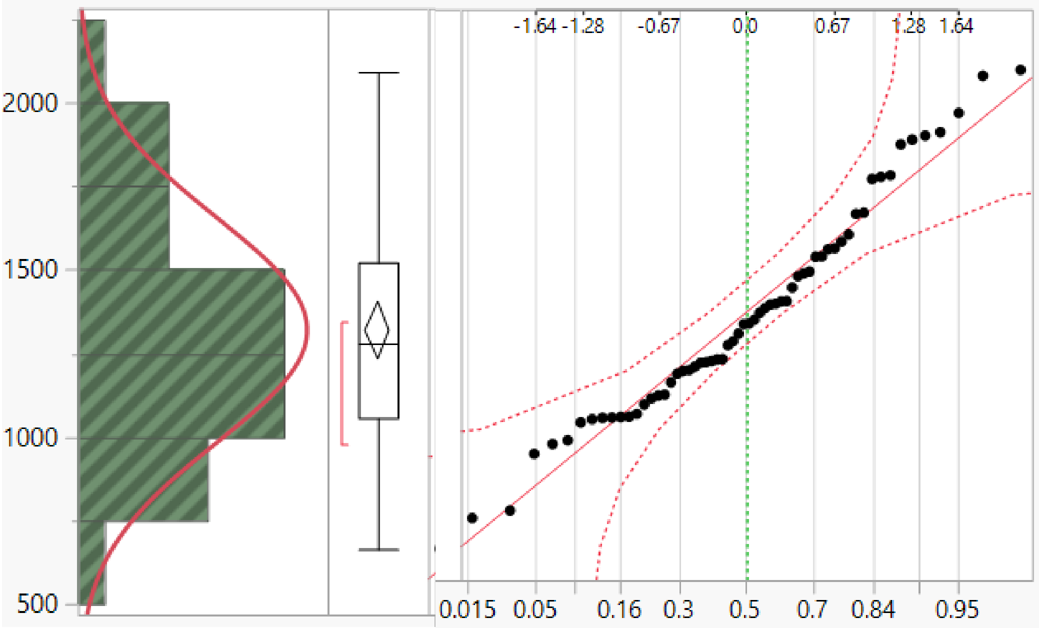
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure (psi)	2	9624987	4812493	21.7177	<.0001*
Error	57	12630814	221593		
C. Total	59	22255801			

Level				Mean
5	A			2424.6000
50		B		1982.9000
100			C	1445.1000

7+ Days – EPI – Load at Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.966753	0.1011

Variances

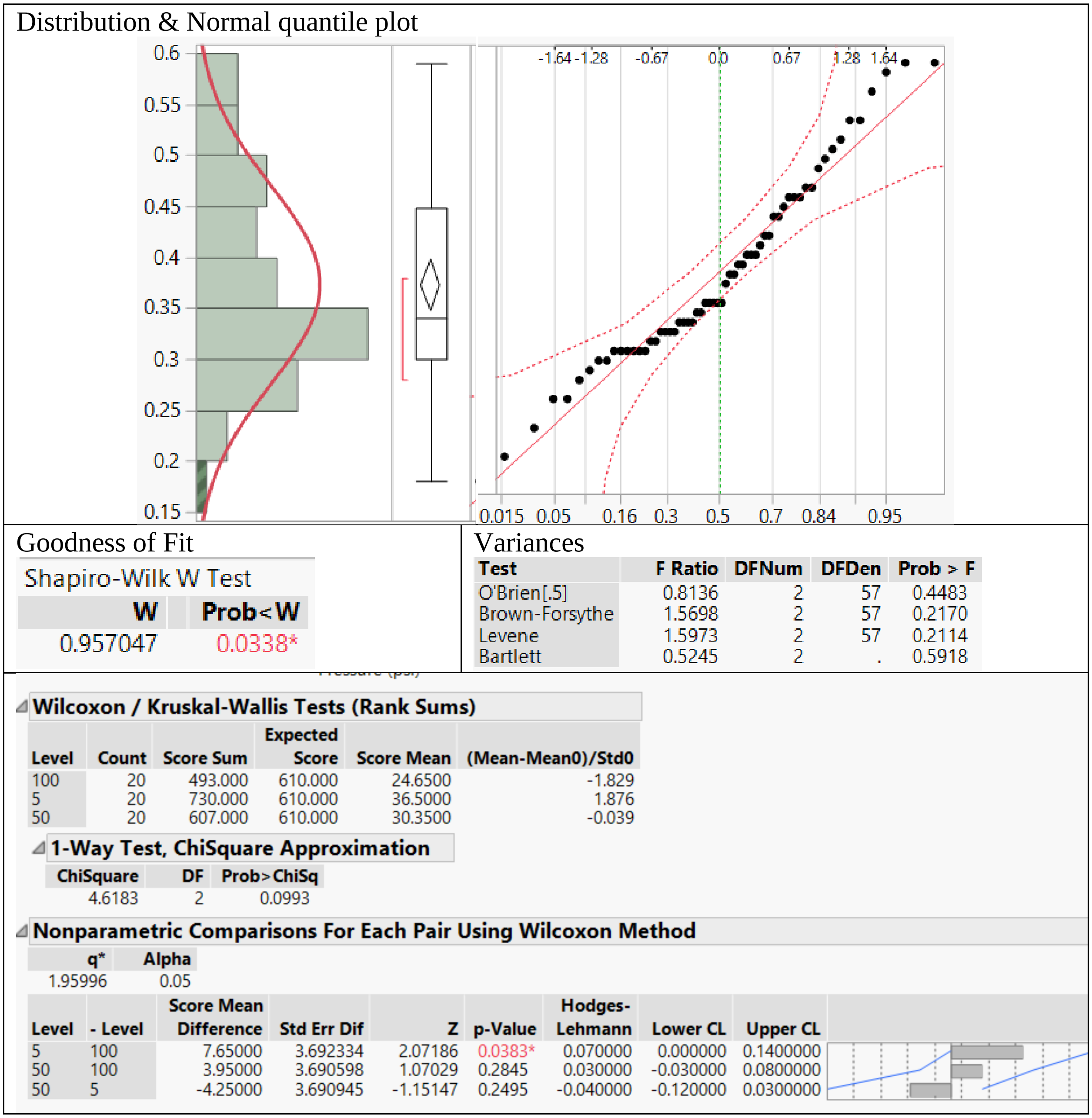
Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.1241	2	57	0.3320
Brown-Forsythe	0.7746	2	57	0.4657
Levene	1.2040	2	57	0.3075
Bartlett	0.8998	2	.	0.4066

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure (psi)	2	549068.4	274534	2.5716	0.0853
Error	57	6085143.3	106757		
C. Total	59	6634211.7			

Level		Mean
5	A	1398.9500
50	A	1375.1000
100	A	1185.1500

7+ Days – SBCA – Deformation at Failure



Distribution & Normal quantile plot

Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.957047	0.0338*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.8136	2	57	0.4483
Brown-Forsythe	1.5698	2	57	0.2170
Levene	1.5973	2	57	0.2114
Bartlett	0.5245	2	.	0.5918

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	493.000	610.000	24.6500	-1.829
5	20	730.000	610.000	36.5000	1.876
50	20	607.000	610.000	30.3500	-0.039

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
4.6183	2	0.0993

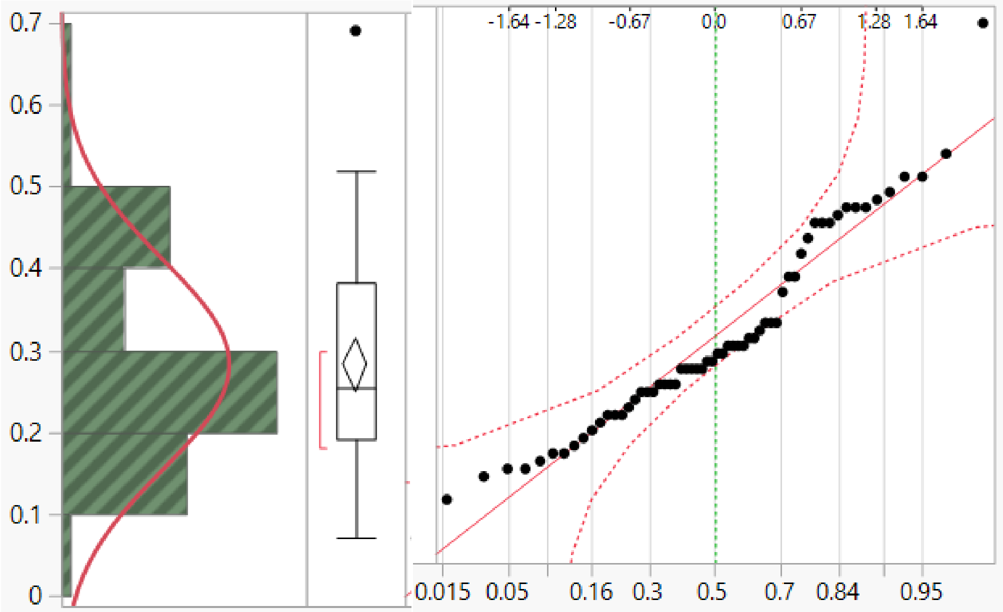
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	7.65000	3.692334	2.07186	0.0383*	0.070000	0.000000	0.1400000
50	100	3.95000	3.690598	1.07029	0.2845	0.030000	-0.030000	0.0800000
50	5	-4.25000	3.690945	-1.15147	0.2495	-0.040000	-0.120000	0.0300000

7+ Days – EPI – Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.942291	0.0069*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.4393	2	57	0.2456
Brown-Forsythe	1.4247	2	57	0.2490
Levene	2.0081	2	57	0.1436
Bartlett	3.3216	2	.	0.0361*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	929.500	610.000	46.4750	5.007
5	20	408.500	610.000	20.4250	-3.155
50	20	492.000	610.000	24.6000	-1.844

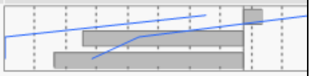
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
25.7211	2	<.0001*

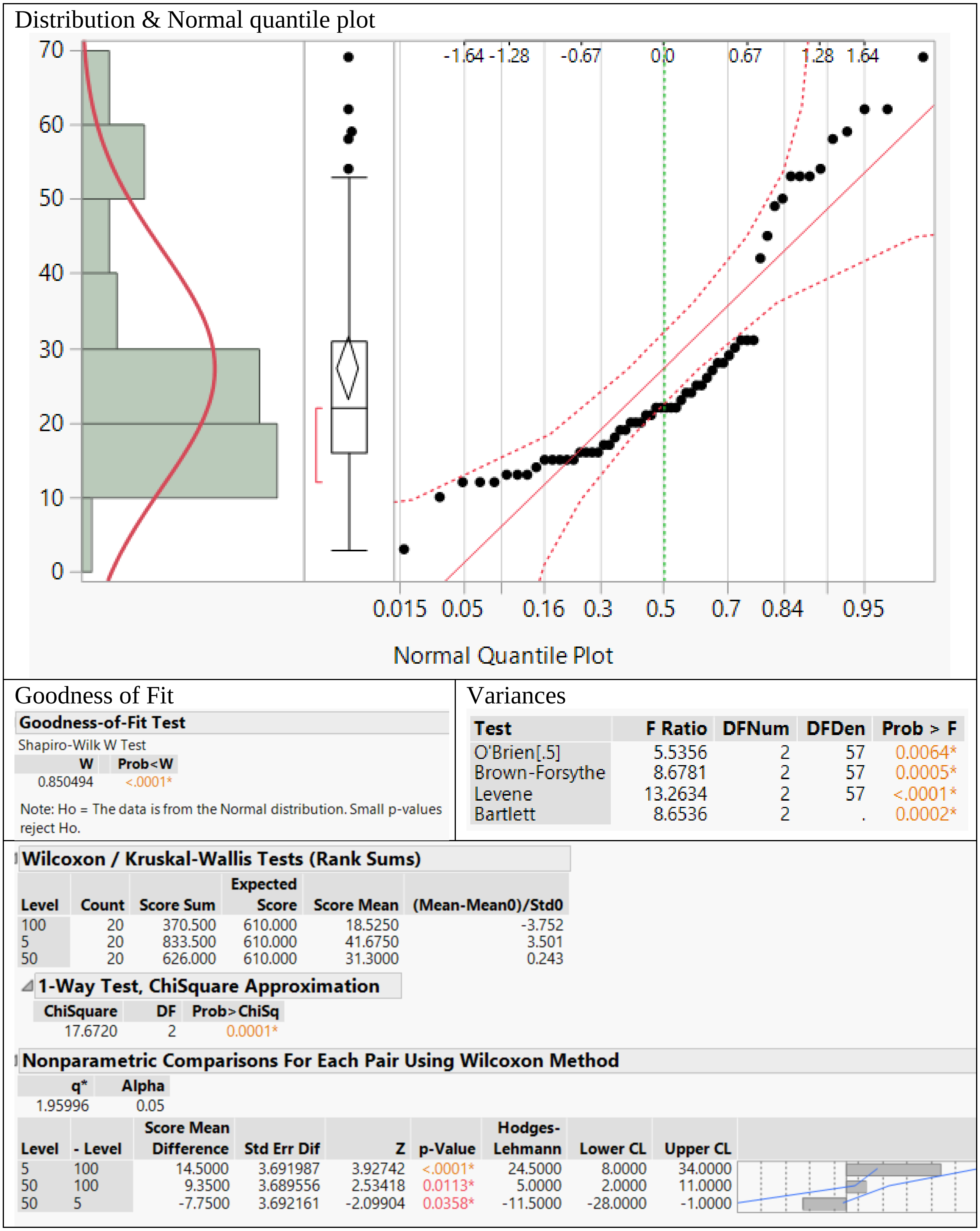
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	5	2.8500	3.692334	0.77187	0.4402	0.020000	-0.040000	0.070000
50	100	-14.6500	3.693549	-3.96637	<.0001*	-0.170000	-0.250000	-0.110000
5	100	-17.2000	3.689034	-4.66247	<.0001*	-0.200000	-0.250000	-0.160000



7+ Days – SBCA –Energy



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.850494	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	5.5356	2	57	0.0064*
Brown-Forsythe	8.6781	2	57	0.0005*
Levene	13.2634	2	57	<.0001*
Bartlett	8.6536	2	.	0.0002*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	370.500	610.000	18.5250	-3.752
5	20	833.500	610.000	41.6750	3.501
50	20	626.000	610.000	31.3000	0.243

1-Way Test, ChiSquare Approximation

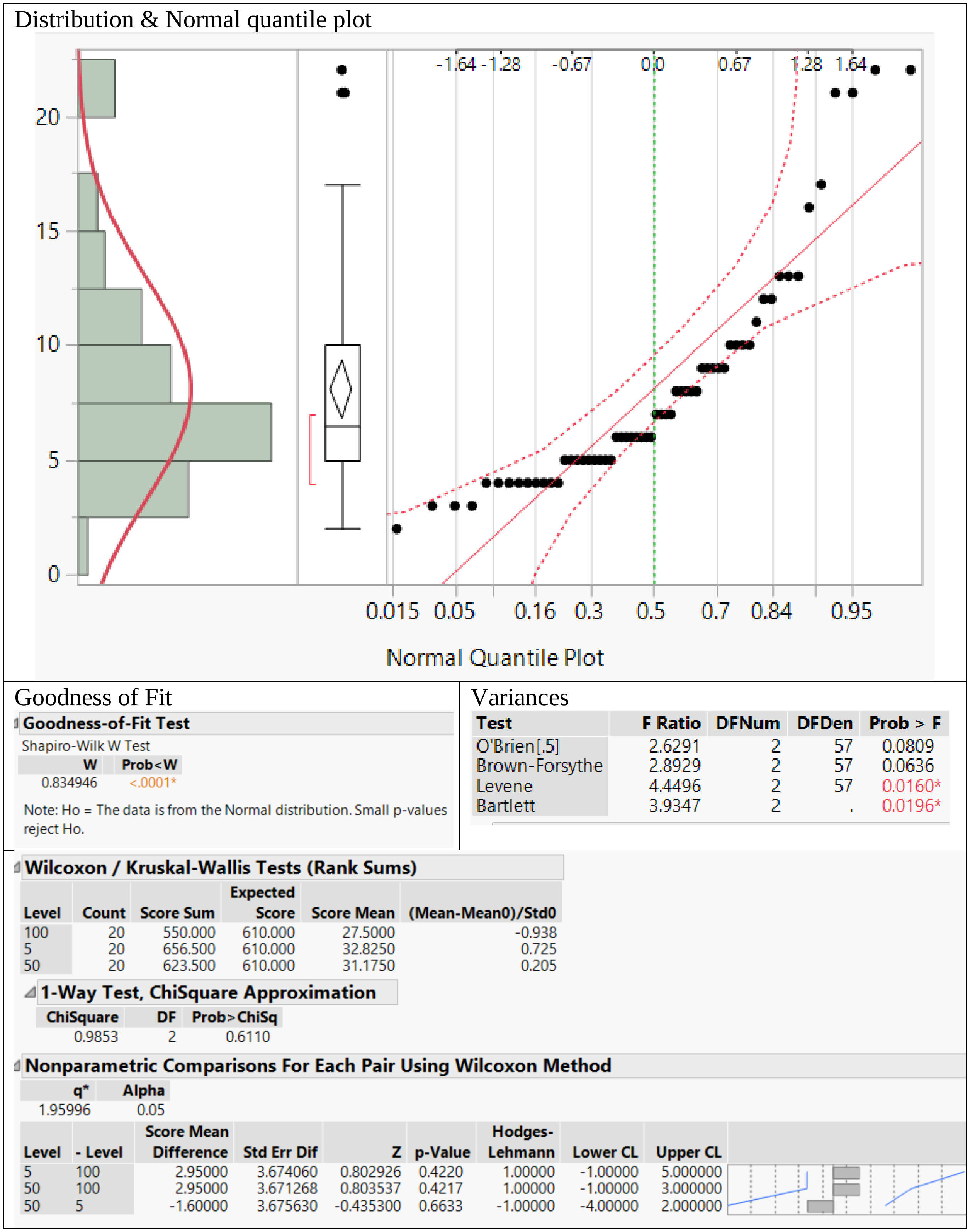
ChiSquare	DF	Prob>ChiSq
17.6720	2	0.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	14.5000	3.691987	3.92742	<.0001*	24.5000	8.0000	34.0000
50	100	9.3500	3.689556	2.53418	0.0113*	5.0000	2.0000	11.0000
50	5	-7.7500	3.692161	-2.09904	0.0358*	-11.5000	-28.0000	-1.0000

7+ Days – EPI –Energy



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.834946	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.6291	2	57	0.0809
Brown-Forsythe	2.8929	2	57	0.0636
Levene	4.4496	2	57	0.0160*
Bartlett	3.9347	2	.	0.0196*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	550.000	610.000	27.5000	-0.938
5	20	656.500	610.000	32.8250	0.725
50	20	623.500	610.000	31.1750	0.205

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.9853	2	0.6110

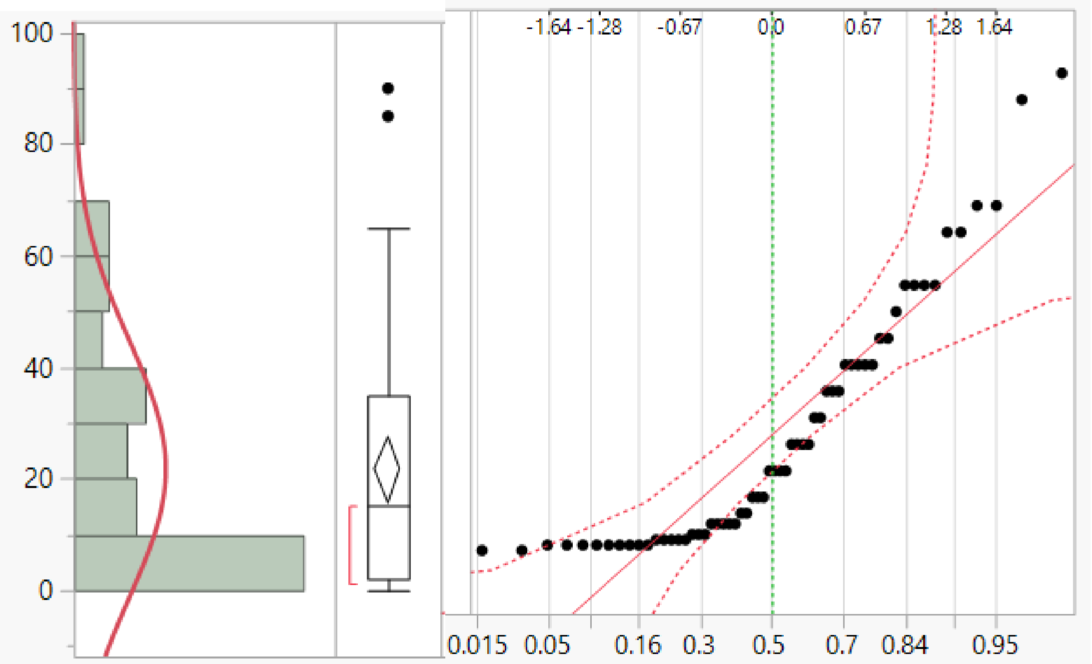
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	2.95000	3.674060	0.802926	0.4220	1.00000	-1.00000	5.000000
50	100	2.95000	3.671268	0.803537	0.4217	1.00000	-1.00000	3.000000
50	5	-1.60000	3.675630	-0.435300	0.6633	-1.00000	-4.00000	2.000000

7+ Days – SBCA –Wood Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.848534	<.0001*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.0573	2	57	0.3541
Brown-Forsythe	1.7543	2	57	0.1822
Levene	1.4274	2	57	0.2484
Bartlett	1.6492	2	.	0.1922

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

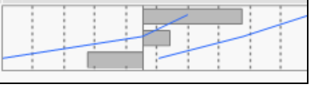
Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	425.000	610.000	21.2500	-2.902
5	20	781.500	610.000	39.0750	2.690
50	20	623.500	610.000	31.1750	0.205

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
10.5289	2	0.0052*

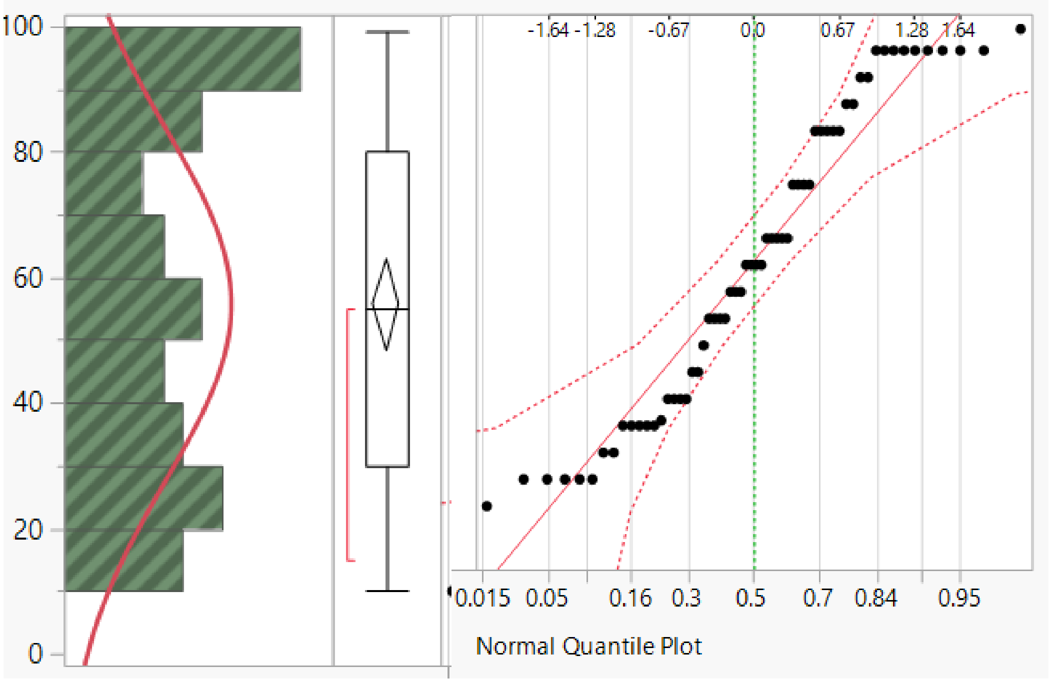
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL	
5	100	11.3000	3.682948	3.06819	0.0022*	18.0000	8.0000	30.00000	
50	100	7.1000	3.676502	1.93118	0.0535	5.0000	0.0000	18.00000	
50	5	-5.7500	3.686775	-1.55963	0.1188	-10.0000	-25.0000	3.00000	

7+ Days – EPI –Wood Failure

Distribution & Normal quantile plot



Goodness of Fit

Shapiro-Wilk W Test

W	Prob<W
0.922767	0.0010*

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.5700	2	57	0.2169
Brown-Forsythe	1.0715	2	57	0.3493
Levene	1.4784	2	57	0.2366
Bartlett	0.9065	2	.	0.4039

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	736.000	610.000	36.8000	1.975
5	20	480.500	610.000	24.0250	-2.030
50	20	613.500	610.000	30.6750	0.047

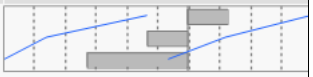
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
5.3910	2	0.0675

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

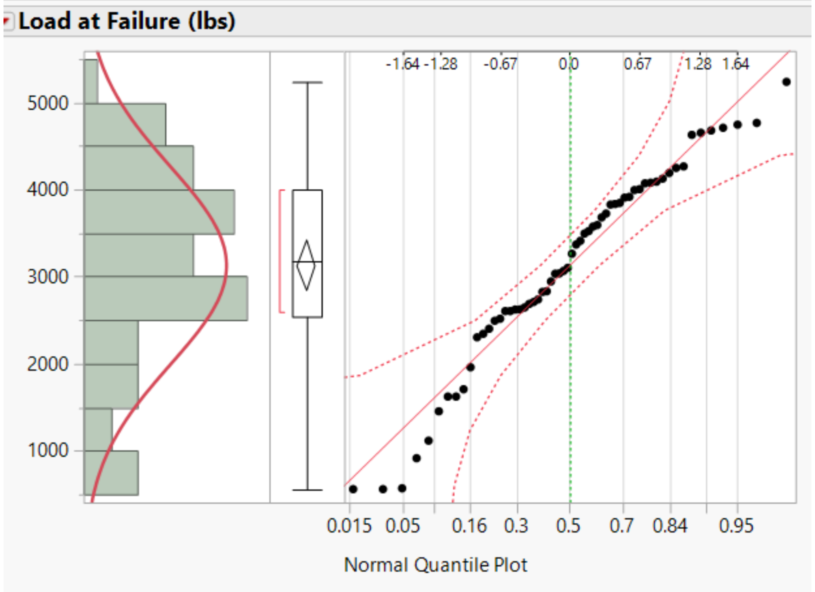
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	5	3.85000	3.685383	1.04467	0.2962	10.0000	-10.0000	30.0000
50	100	-3.50000	3.669870	-0.95371	0.3402	-10.0000	-35.0000	9.0000
5	100	-9.00000	3.680858	-2.44508	0.0145*	-25.0000	-45.0000	-5.0000



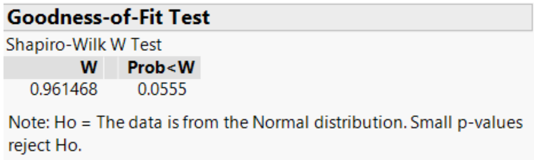
5.4 Appendix D – Statistics for the effect of pre-compression pressure on the shear strength of the connection

7+ Days – SBCA –Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



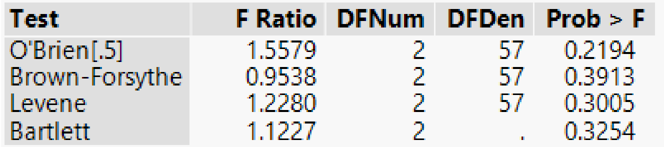
Goodness-of-Fit Test

Shapiro-Wilk W Test

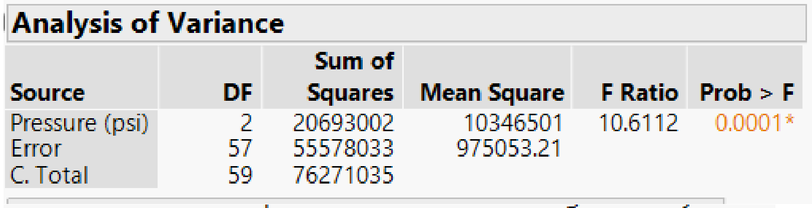
W	Prob<W
0.961468	0.0555

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

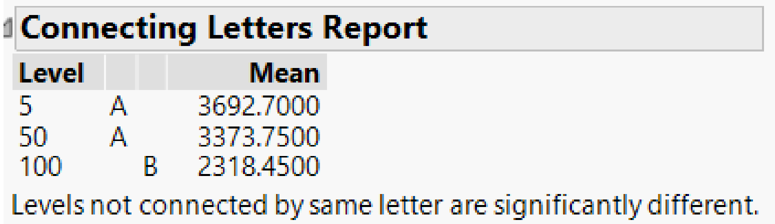


Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.5579	2	57	0.2194
Brown-Forsythe	0.9538	2	57	0.3913
Levene	1.2280	2	57	0.3005
Bartlett	1.1227	2	.	0.3254



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure (psi)	2	20693002	10346501	10.6112	0.0001*
Error	57	55578033	975053.21		
C. Total	59	76271035			



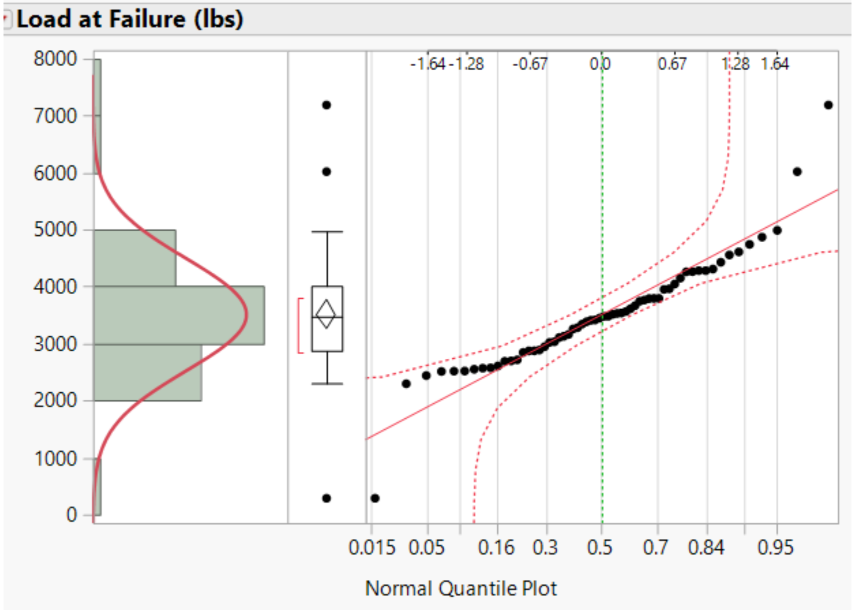
Connecting Letters Report

Level			Mean
5	A		3692.7000
50	A		3373.7500
100		B	2318.4500

Levels not connected by same letter are significantly different.

7+ Days – EPI –Load at Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.921923	0.0009*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.5575	2	57	0.5757
Brown-Forsythe	0.3582	2	57	0.7005
Levene	0.3786	2	57	0.6865
Bartlett	2.1447	2	.	0.1171

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	584.500	610.000	29.2250	-0.392
5	20	751.500	610.000	37.5750	2.211
50	20	494.000	610.000	24.7000	-1.811

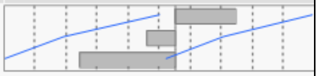
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
5.5951	2	0.0610

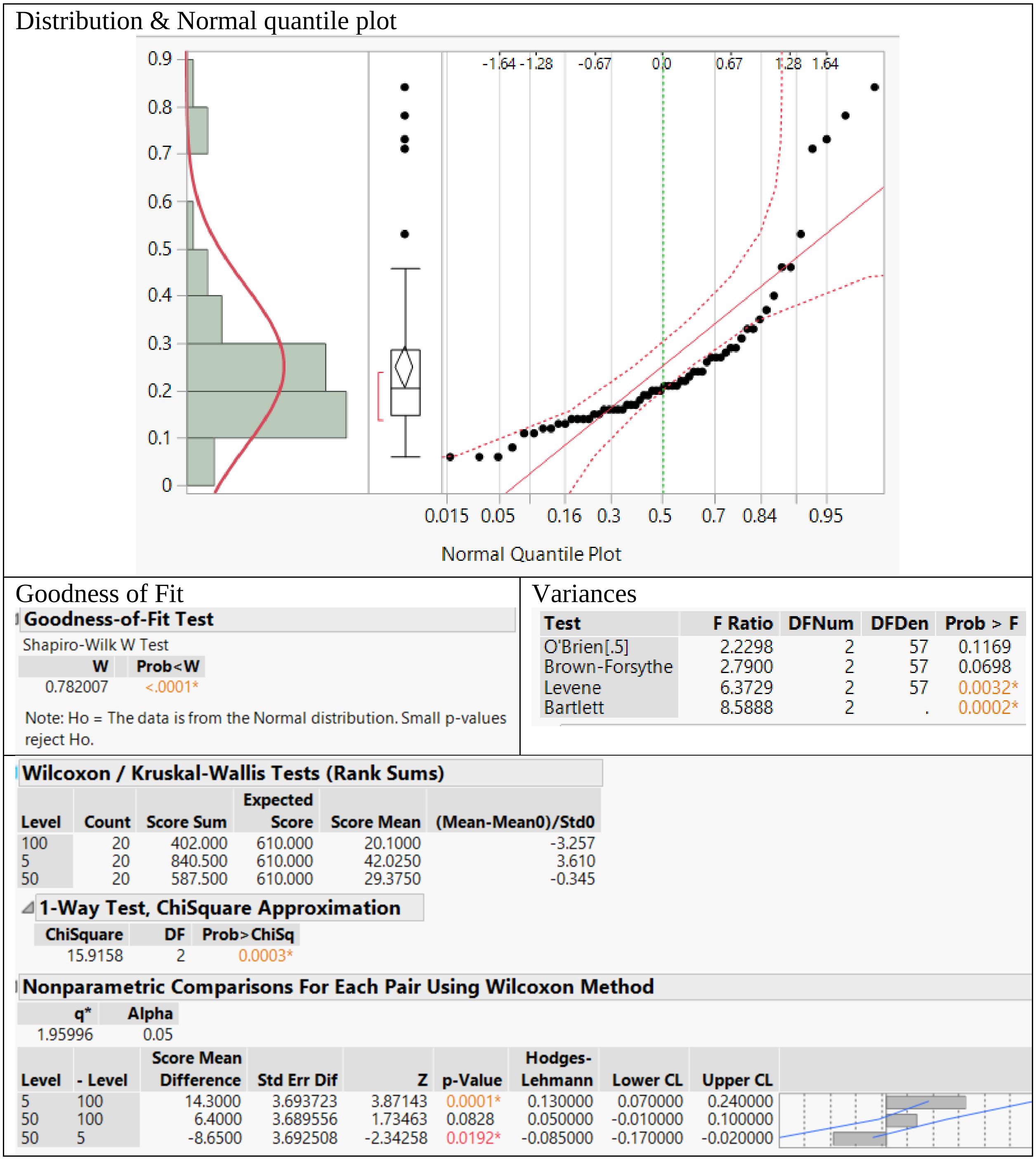
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	5.60000	3.696499	1.51495	0.1298	402.500	-101.00	889.000
50	100	-3.05000	3.696672	-0.82507	0.4093	-184.500	-720.00	319.000
50	5	-8.45000	3.696846	-2.28573	0.0223*	-623.500	-1099.00	-58.000



7+ Days – SBCA –Deformation at Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.782007	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.2298	2	57	0.1169
Brown-Forsythe	2.7900	2	57	0.0698
Levene	6.3729	2	57	0.0032*
Bartlett	8.5888	2	.	0.0002*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	402.000	610.000	20.1000	-3.257
5	20	840.500	610.000	42.0250	3.610
50	20	587.500	610.000	29.3750	-0.345

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
15.9158	2	0.0003*

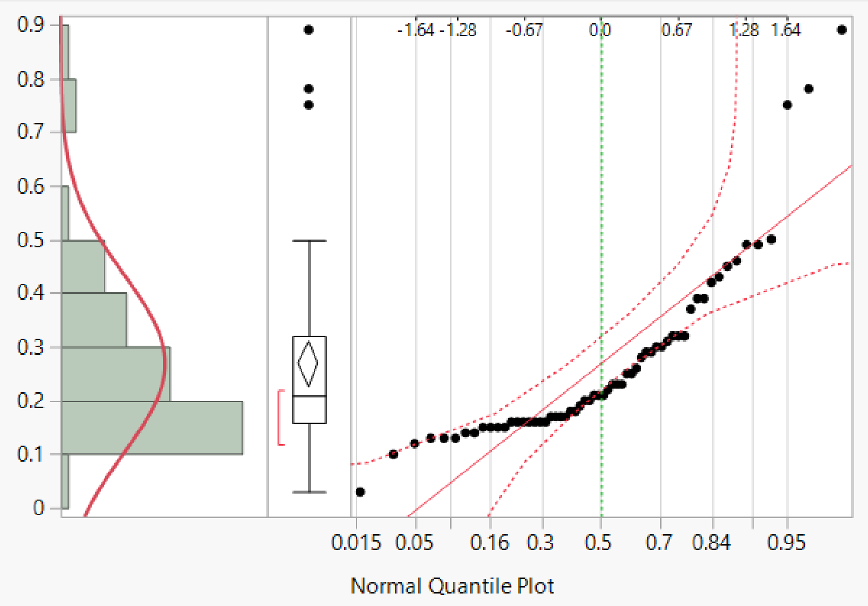
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

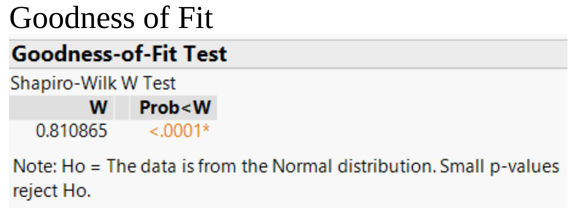
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	14.3000	3.693723	3.87143	0.0001*	0.130000	0.070000	0.240000
50	100	6.4000	3.689556	1.73463	0.0828	0.050000	-0.010000	0.100000
50	5	-8.6500	3.692508	-2.34258	0.0192*	-0.085000	-0.170000	-0.020000

7+ Days – EPI –Deformation at Failure

Distribution & Normal quantile plot





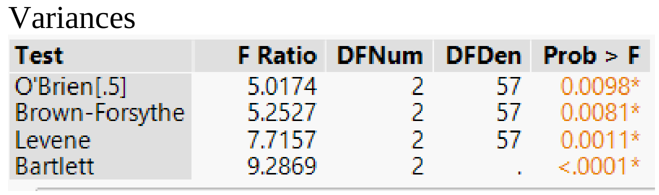
Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

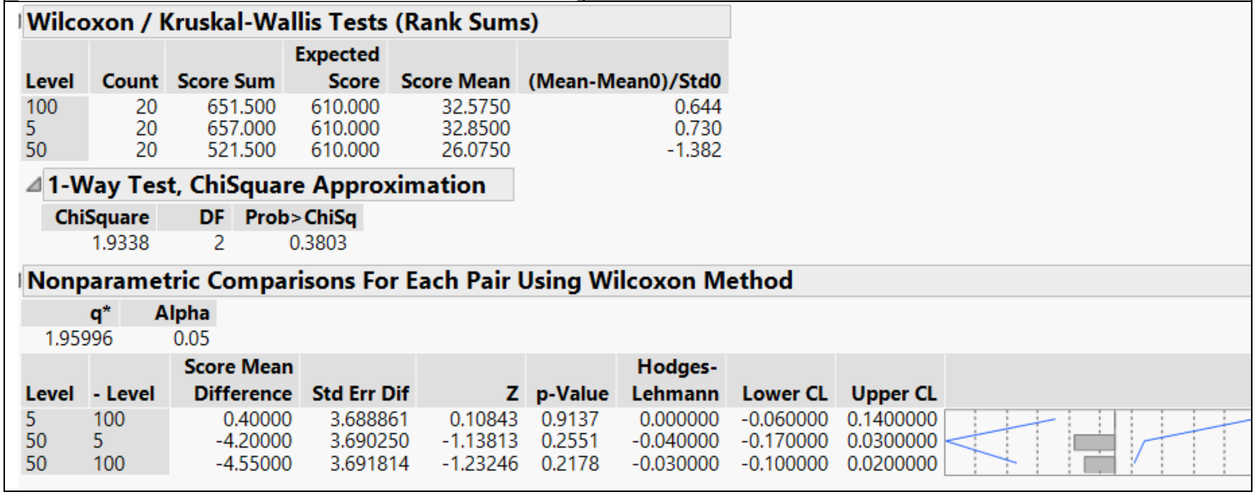
W	Prob<W
0.810865	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.



Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	5.0174	2	57	0.0098*
Brown-Forsythe	5.2527	2	57	0.0081*
Levene	7.7157	2	57	0.0011*
Bartlett	9.2869	2	.	<.0001*



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	651.500	610.000	32.5750	0.644
5	20	657.000	610.000	32.8500	0.730
50	20	521.500	610.000	26.0750	-1.382

1-Way Test, ChiSquare Approximation

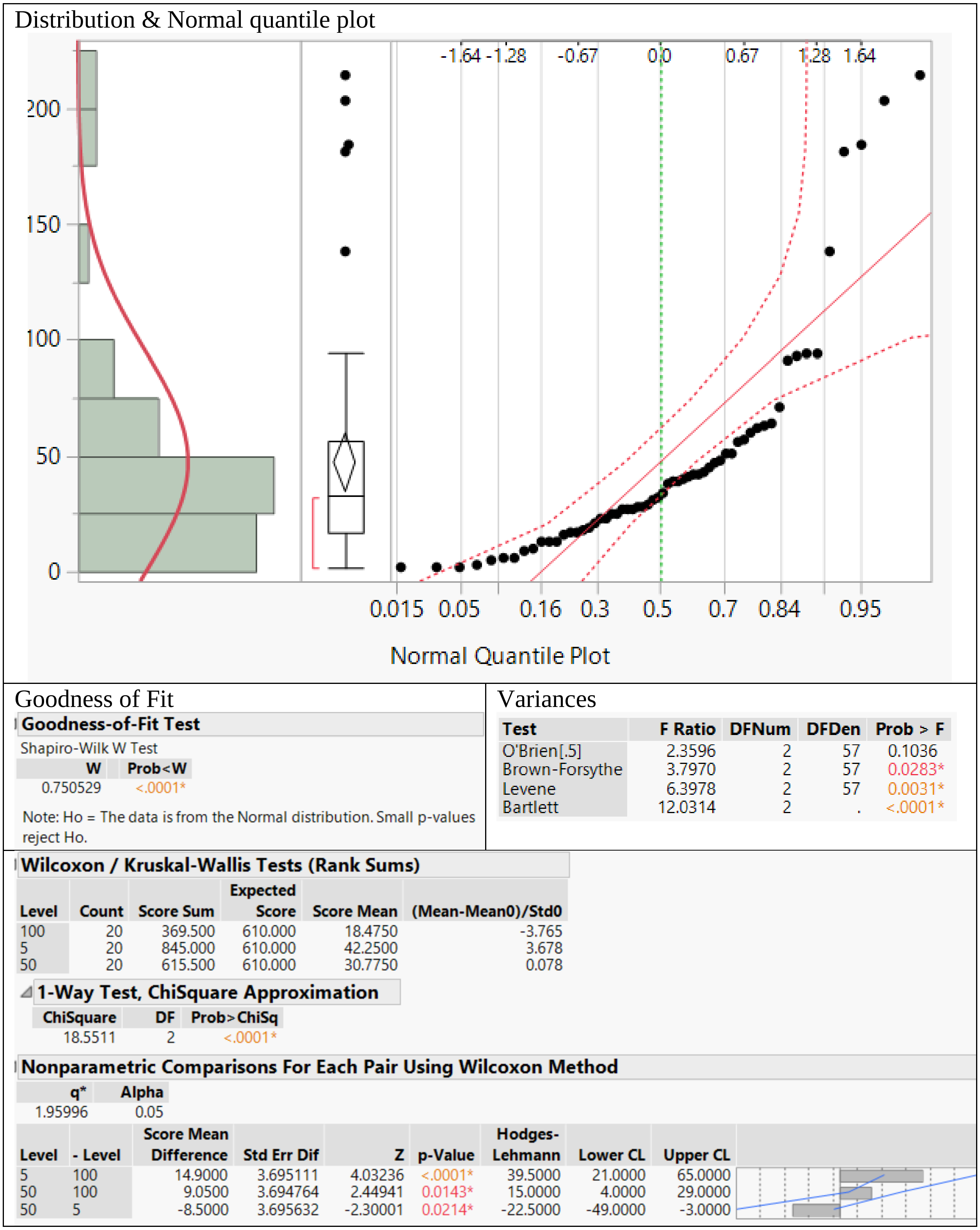
ChiSquare	DF	Prob>ChiSq
1.9338	2	0.3803

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	0.40000	3.688861	0.10843	0.9137	0.000000	-0.060000	0.1400000
50	5	-4.20000	3.690250	-1.13813	0.2551	-0.040000	-0.170000	0.0300000
50	100	-4.55000	3.691814	-1.23246	0.2178	-0.030000	-0.100000	0.0200000

7+ Days – SBCA –Energy



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.750529	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.3596	2	57	0.1036
Brown-Forsythe	3.7970	2	57	0.0283*
Levene	6.3978	2	57	0.0031*
Bartlett	12.0314	2	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	369.500	610.000	18.4750	-3.765
5	20	845.000	610.000	42.2500	3.678
50	20	615.500	610.000	30.7750	0.078

1-Way Test, ChiSquare Approximation

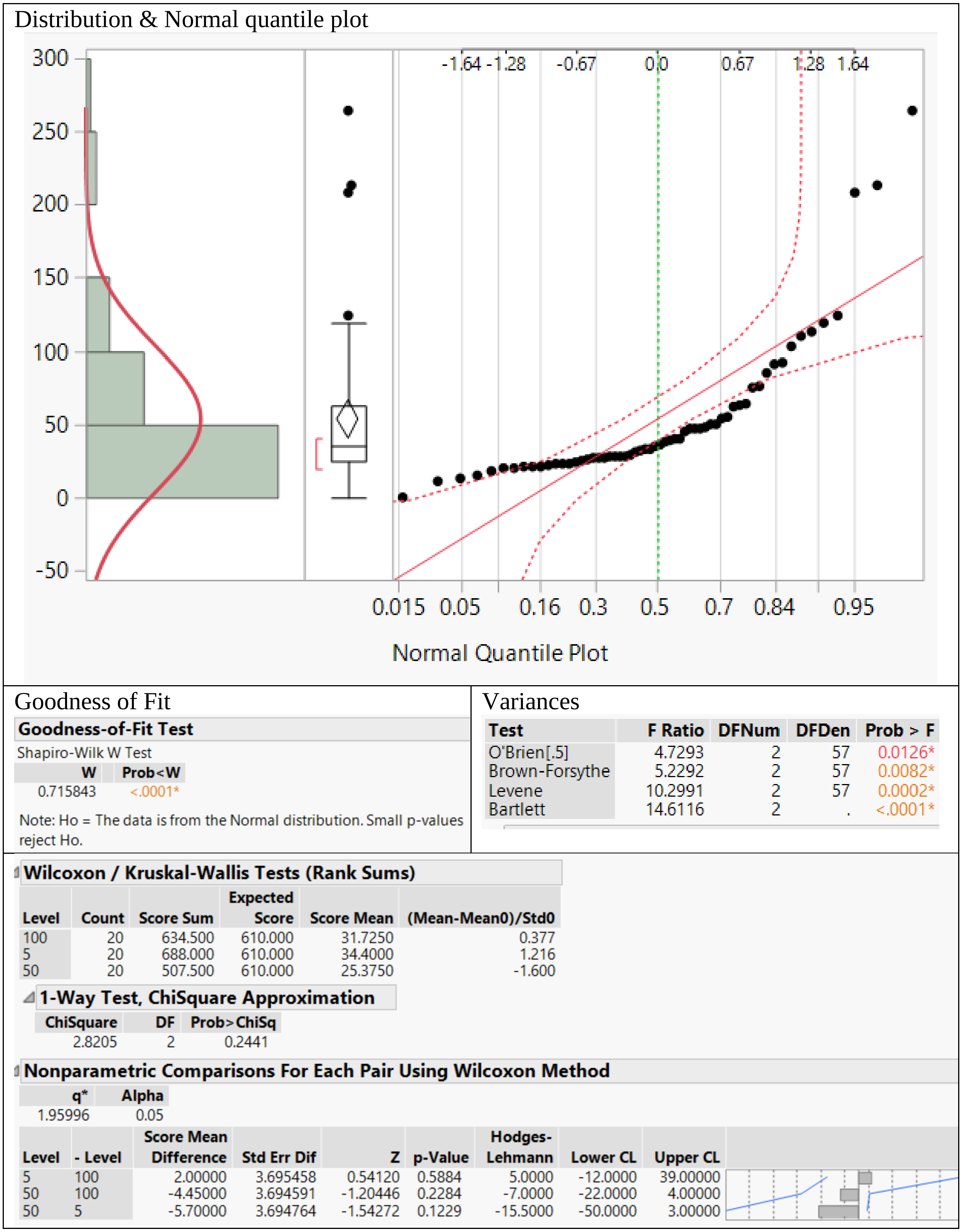
ChiSquare	DF	Prob>ChiSq
18.5511	2	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	14.9000	3.695111	4.03236	<.0001*	39.5000	21.0000	65.0000
50	100	9.0500	3.694764	2.44941	0.0143*	15.0000	4.0000	29.0000
50	5	-8.5000	3.695632	-2.30001	0.0214*	-22.5000	-49.0000	-3.0000

7+ Days – EPI –Energy



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.715843	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	4.7293	2	57	0.0126*
Brown-Forsythe	5.2292	2	57	0.0082*
Levene	10.2991	2	57	0.0002*
Bartlett	14.6116	2	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	20	634.500	610.000	31.7250	0.377
5	20	688.000	610.000	34.4000	1.216
50	20	507.500	610.000	25.3750	-1.600

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
2.8205	2	0.2441

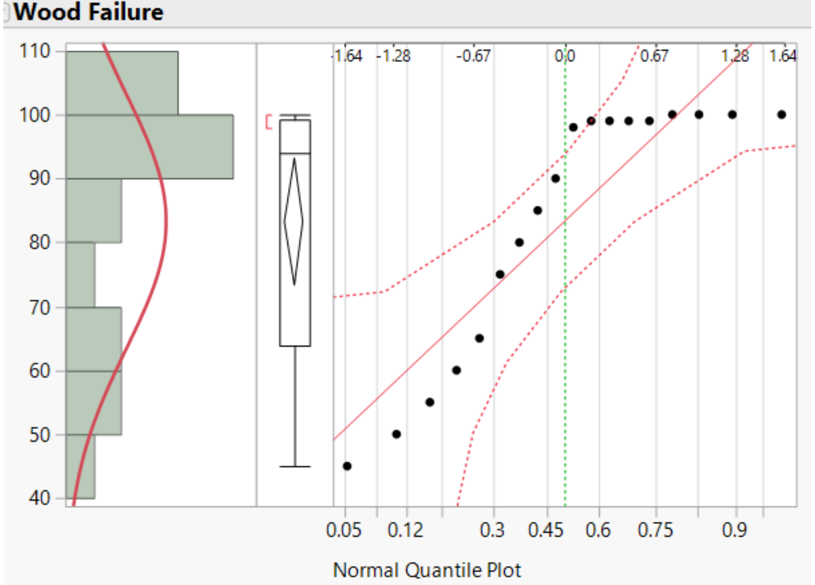
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

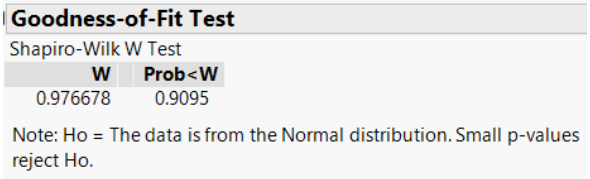
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
5	100	2.00000	3.695458	0.54120	0.5884	5.0000	-12.0000	39.00000
50	100	-4.45000	3.694591	-1.20446	0.2284	-7.0000	-22.0000	4.00000
50	5	-5.70000	3.694764	-1.54272	0.1229	-15.5000	-50.0000	3.00000

7+ Days – SBCA –Compression Wood Failure

Distribution & Normal quantile plot



Goodness of Fit



Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.976678	0.9095

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

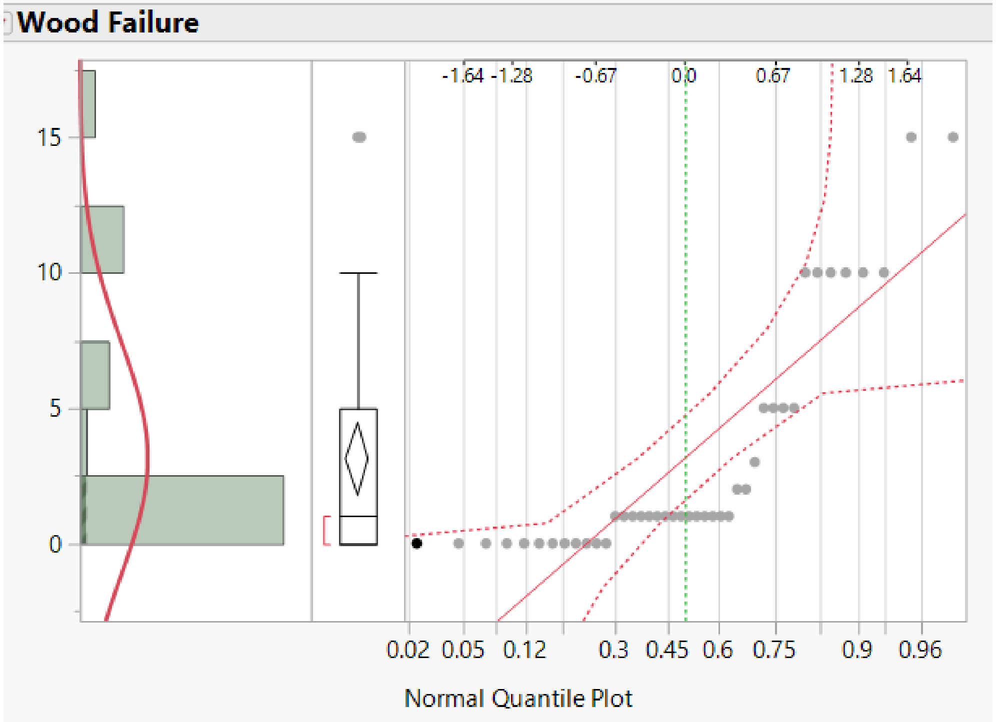
Variances

Unable to conduct more tests due to only one sample in two groups

7+ Days – SBCA –Shear Wood Failure

Distribution & Normal quantile plot

Wood Failure



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.712935	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	4.2906	2	39	0.0207*
Brown-Forsythe	2.8263	2	39	0.0714
Levene	5.9874	2	39	0.0054*
Bartlett	3.0679	2	.	0.0465*

Warning: Small sample sizes. Use Caution.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	19	384.500	408.500	20.2368	-0.617
5	4	92.000	86.000	23.0000	0.245
50	19	426.500	408.500	22.4474	0.459

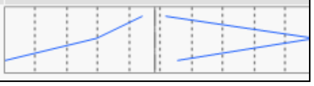
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.4038	2	0.8172

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

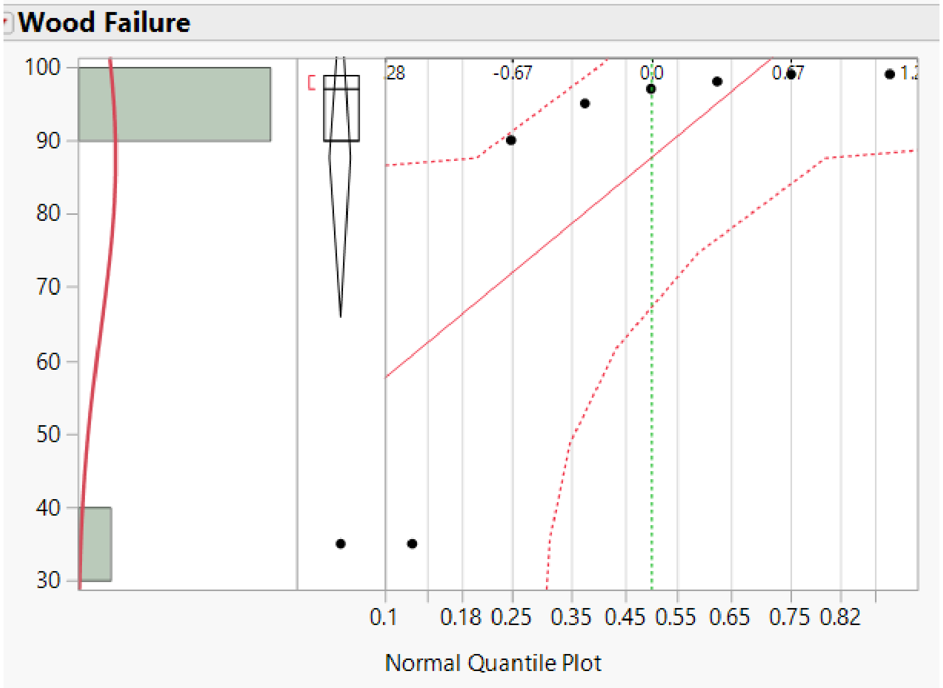
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	100	2.05263	3.453203	0.594414	0.5522	0	-1.0000	1.00000
5	100	1.05921	3.573853	0.296378	0.7669	0	-5.0000	14.00000
50	5	-0.45395	3.594004	-0.126307	0.8995	0	-13.0000	2.00000

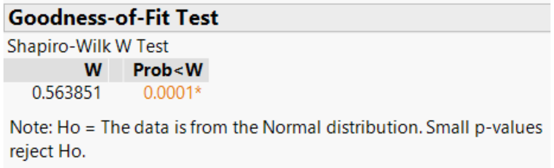


7+ Days – EPI –Compression Wood Failure

Distribution & Normal quantile plot



Goodness of Fit



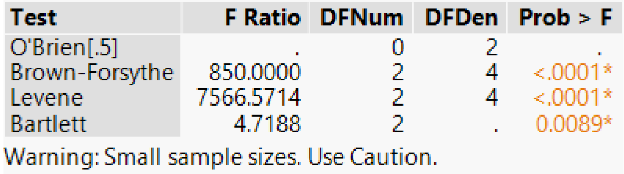
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.563851	0.0001*

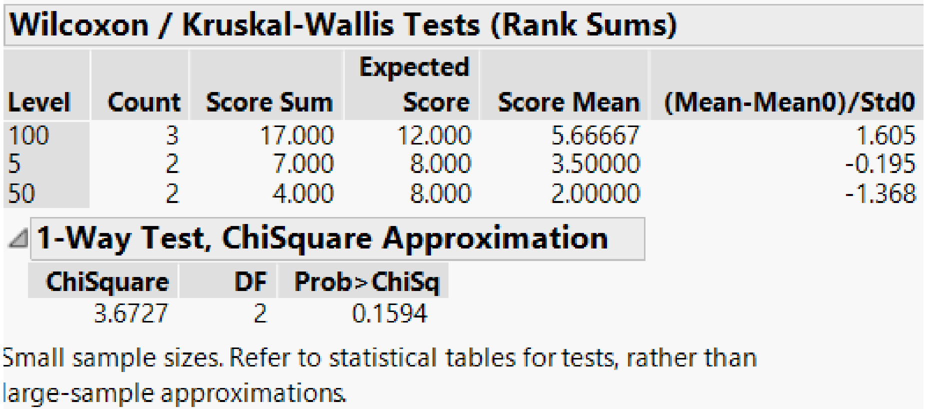
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	.	0	2	.
Brown-Forsythe	850.0000	2	4	<.0001*
Levene	7566.5714	2	4	<.0001*
Bartlett	4.7188	2	.	0.0089*

Warning: Small sample sizes. Use Caution.



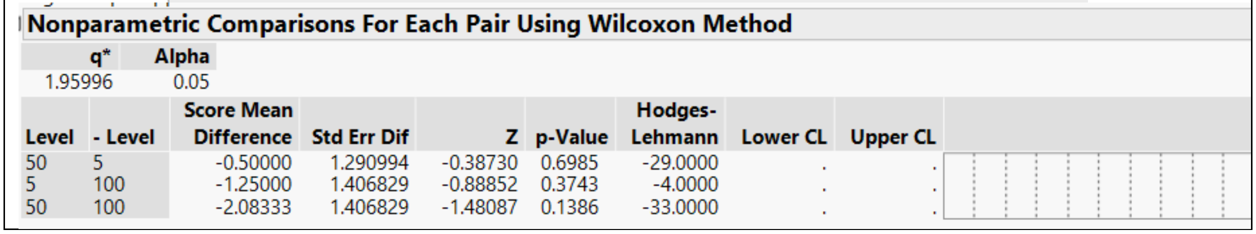
Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
100	3	17.000	12.000	5.66667	1.605
5	2	7.000	8.000	3.50000	-0.195
50	2	4.000	8.000	2.00000	-1.368

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
3.6727	2	0.1594

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.



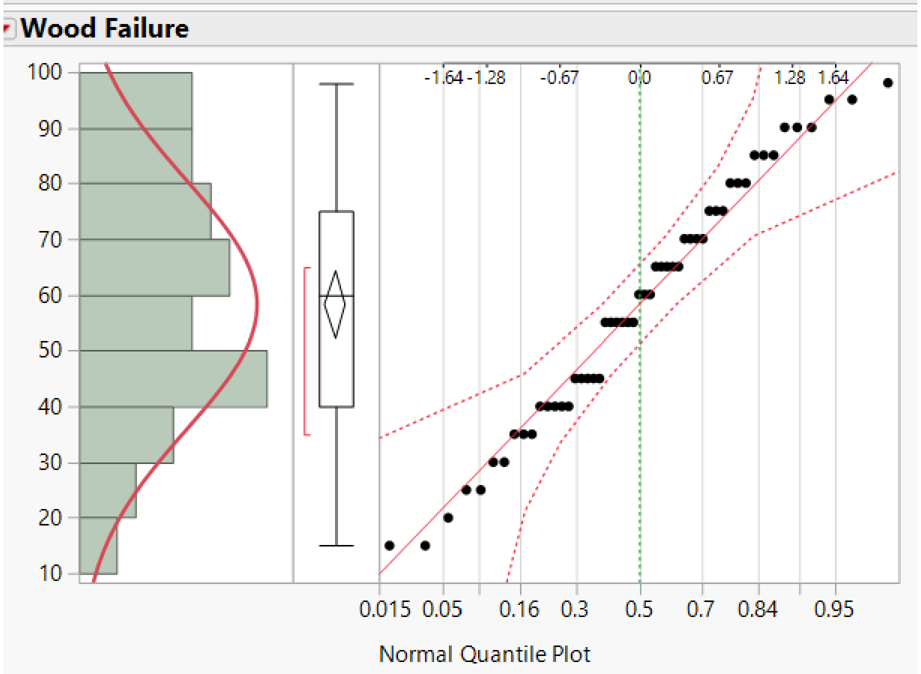
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

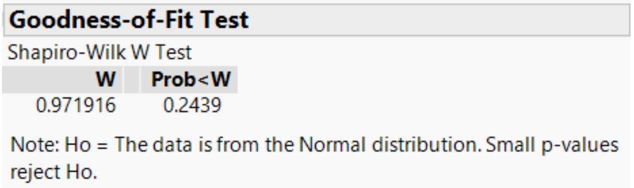
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
50	5	-0.50000	1.290994	-0.38730	0.6985	-29.0000	.	.
5	100	-1.25000	1.406829	-0.88852	0.3743	-4.0000	.	.
50	100	-2.08333	1.406829	-1.48087	0.1386	-33.0000	.	.

7+ Days – EPI –Shear Wood Failure

Distribution & Normal quantile plot



Goodness of Fit



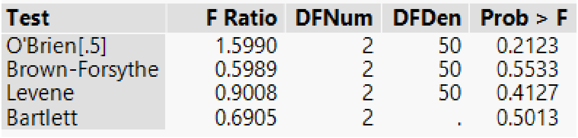
Goodness-of-Fit Test

Shapiro-Wilk W Test

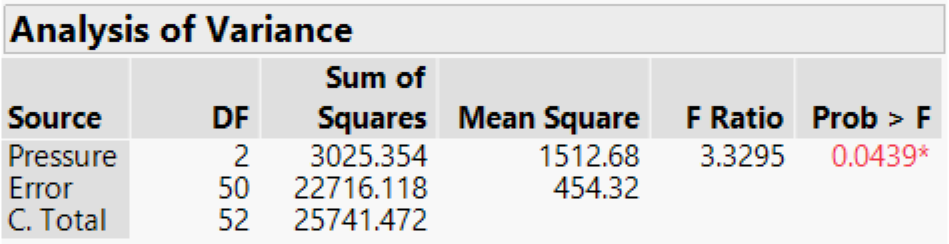
W	Prob<W
0.971916	0.2439

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

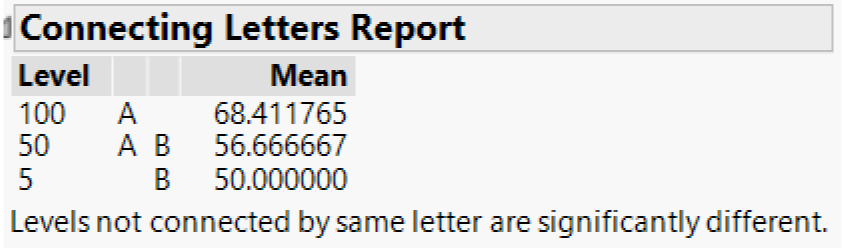


Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.5990	2	50	0.2123
Brown-Forsythe	0.5989	2	50	0.5533
Levene	0.9008	2	50	0.4127
Bartlett	0.6905	2	.	0.5013



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pressure	2	3025.354	1512.68	3.3295	0.0439*
Error	50	22716.118	454.32		
C. Total	52	25741.472			



Connecting Letters Report

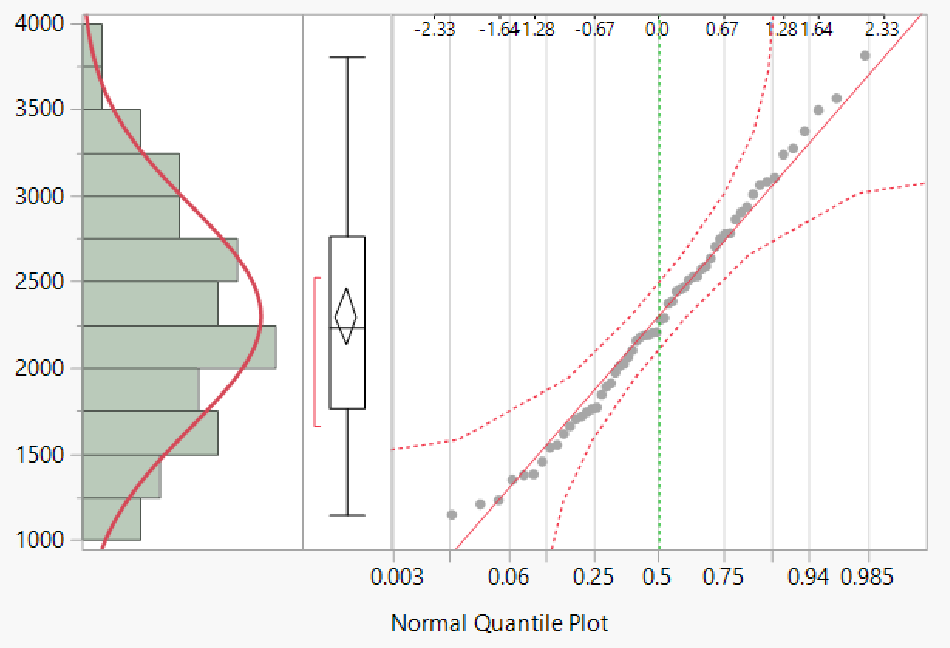
Level			Mean
100	A		68.411765
50	A	B	56.666667
5		B	50.000000

Levels not connected by same letter are significantly different.

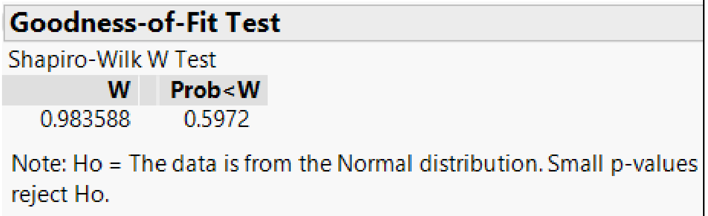
5.5 Appendix E – Statistics for the effect of connection method on the tensile strength perpendicular to the grain of the connection

Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



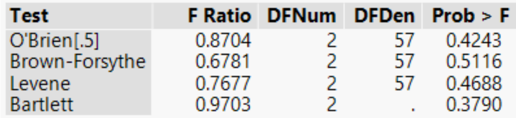
Goodness-of-Fit Test

Shapiro-Wilk W Test

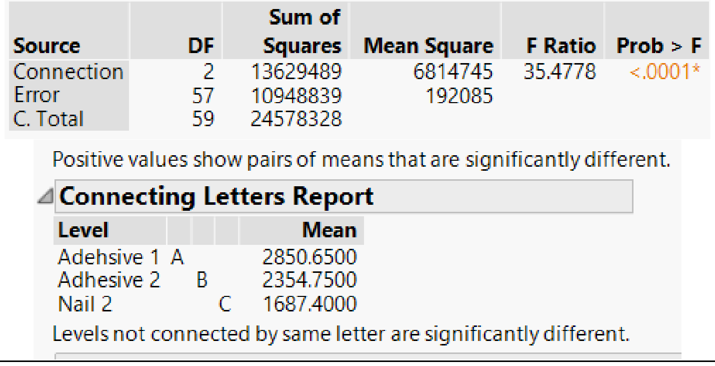
W	Prob<W
0.983588	0.5972

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.8704	2	57	0.4243
Brown-Forsythe	0.6781	2	57	0.5116
Levene	0.7677	2	57	0.4688
Bartlett	0.9703	2	.	0.3790



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Connection	2	13629489	6814745	35.4778	<.0001*
Error	57	10948839	192085		
C. Total	59	24578328			

Positive values show pairs of means that are significantly different.

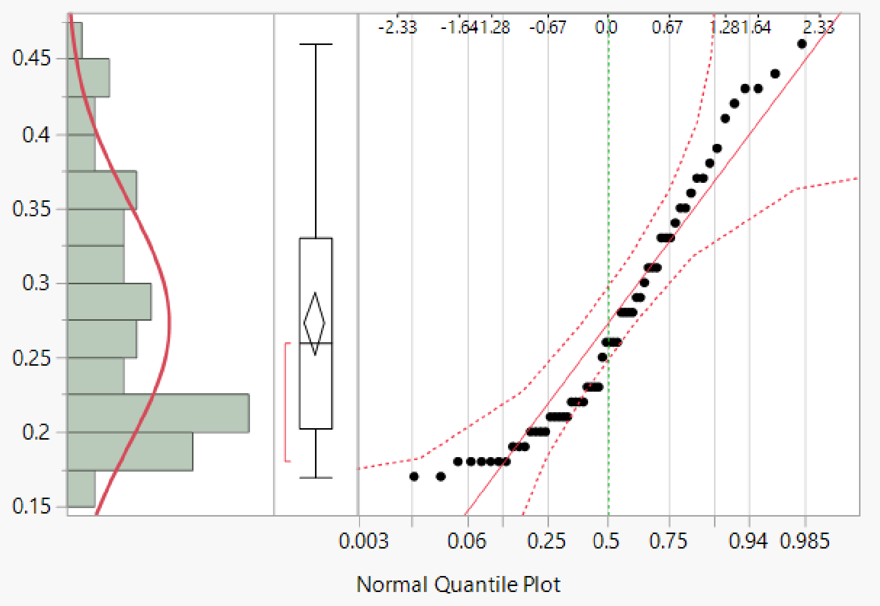
Connecting Letters Report

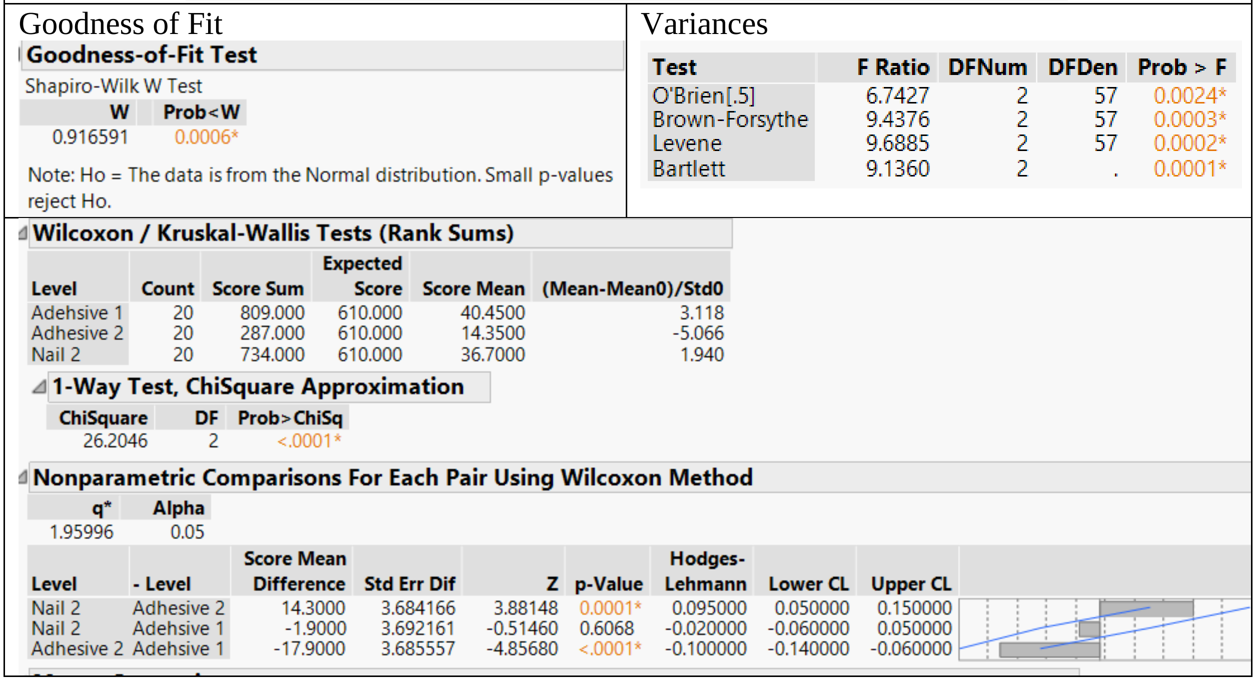
Level				Mean
Adehsive 1	A			2850.6500
Adhesive 2		B		2354.7500
Nail 2			C	1687.4000

Levels not connected by same letter are significantly different.

Deformation at Failure

Distribution & Normal quantile plot





Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.916591	0.0006*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	6.7427	2	57	0.0024*
Brown-Forsythe	9.4376	2	57	0.0003*
Levene	9.6885	2	57	0.0002*
Bartlett	9.1360	2	.	0.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Adehsive 1	20	809.000	610.000	40.4500	3.118
Adehsive 2	20	287.000	610.000	14.3500	-5.066
Nail 2	20	734.000	610.000	36.7000	1.940

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
26.2046	2	<.0001*

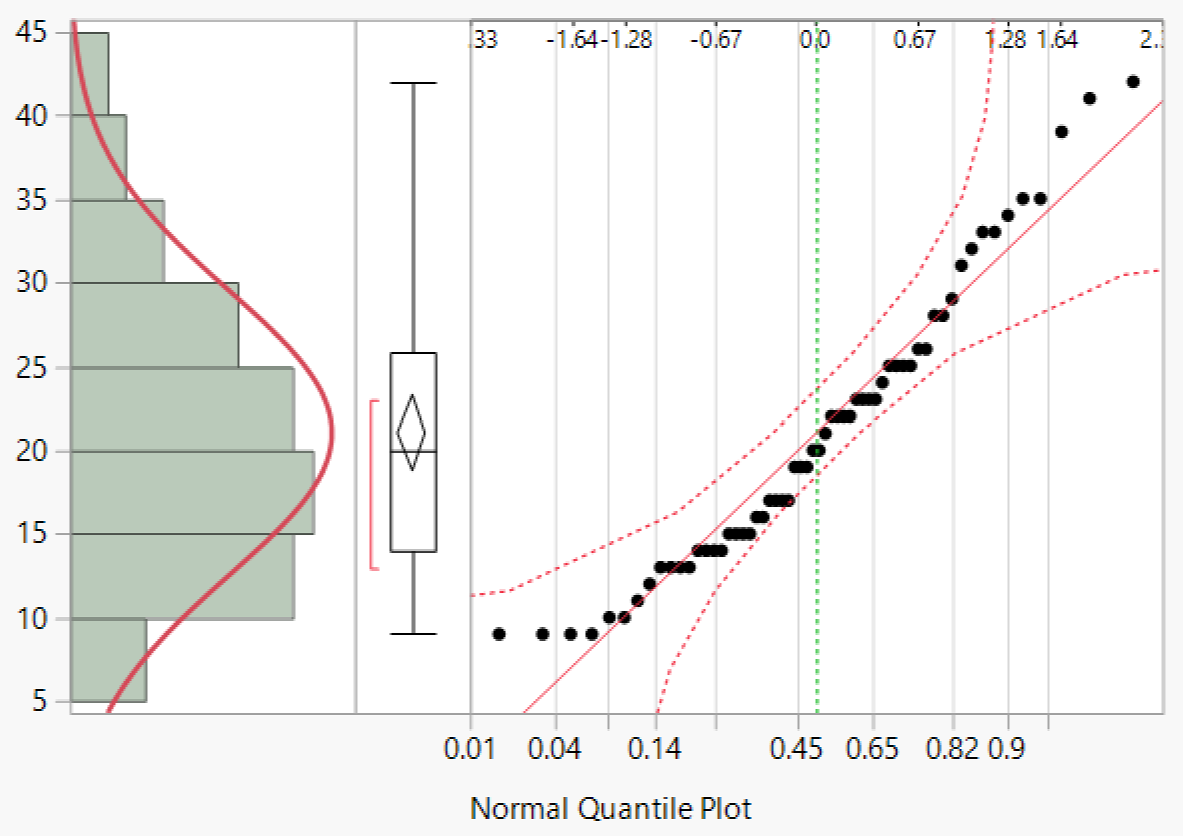
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	Adhesive 2	14.3000	3.684166	3.88148	0.0001*	0.095000	0.050000	0.150000
Nail 2	Adehsive 1	-1.9000	3.692161	-0.51460	0.6068	-0.020000	-0.060000	0.050000
Adhesive 2	Adehsive 1	-17.9000	3.685557	-4.85680	<.0001*	-0.100000	-0.140000	-0.060000

Energy

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.948625	0.0134*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	2.7928	2	57	0.0696
Brown-Forsythe	2.7119	2	57	0.0750
Levene	2.5900	2	57	0.0838
Bartlett	2.4537	2	.	0.0860

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi	20	753.500	610.000	37.6750	2.245
A2 5 psi	20	398.000	610.000	19.9000	-3.321
Nail 2	20	678.500	610.000	33.9250	1.068

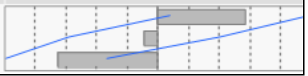
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
11.5421	2	0.0031*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

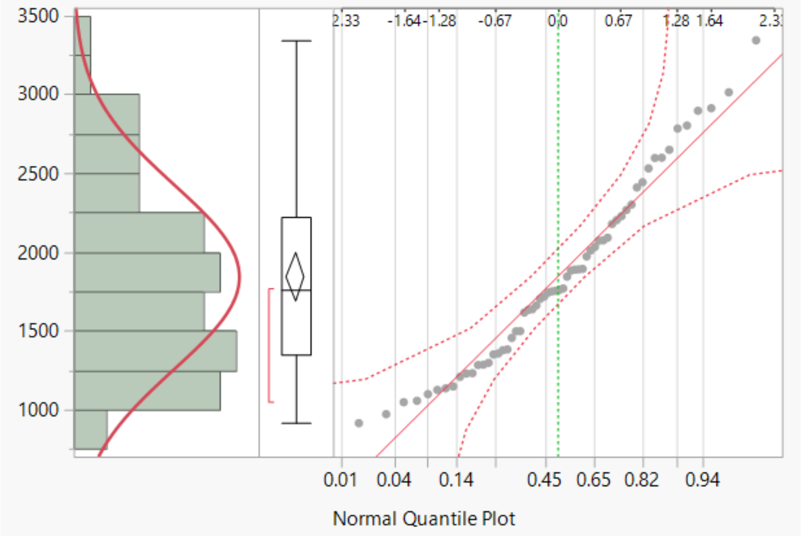
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	A2 5 psi	8.6500	3.690077	2.34412	0.0191*	7.00000	1.0000	12.0000
Nail 2	A1 5 psi	-1.8000	3.693029	-0.48740	0.6260	-1.00000	-7.0000	5.0000
A2 5 psi	A1 5 psi	-12.4500	3.690598	-3.37344	0.0007*	-8.00000	-12.0000	-4.0000



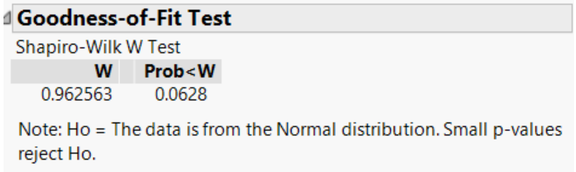
5.6 Appendix F – Statistics for the effect of connection method on the tensile strength parallel to the grain of the connection

Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



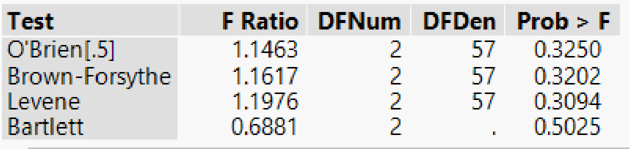
Goodness-of-Fit Test

Shapiro-Wilk W Test

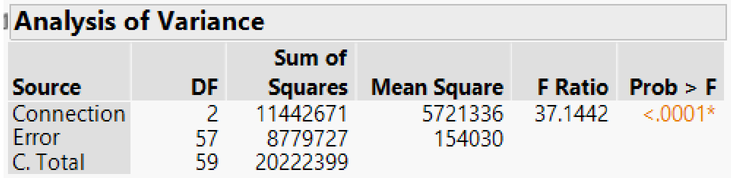
W	Prob<W
0.962563	0.0628

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

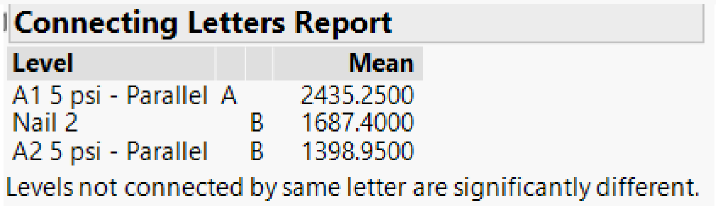


Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	1.1463	2	57	0.3250
Brown-Forsythe	1.1617	2	57	0.3202
Levene	1.1976	2	57	0.3094
Bartlett	0.6881	2	.	0.5025



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Connection	2	11442671	5721336	37.1442	<.0001*
Error	57	8779727	154030		
C. Total	59	20222399			



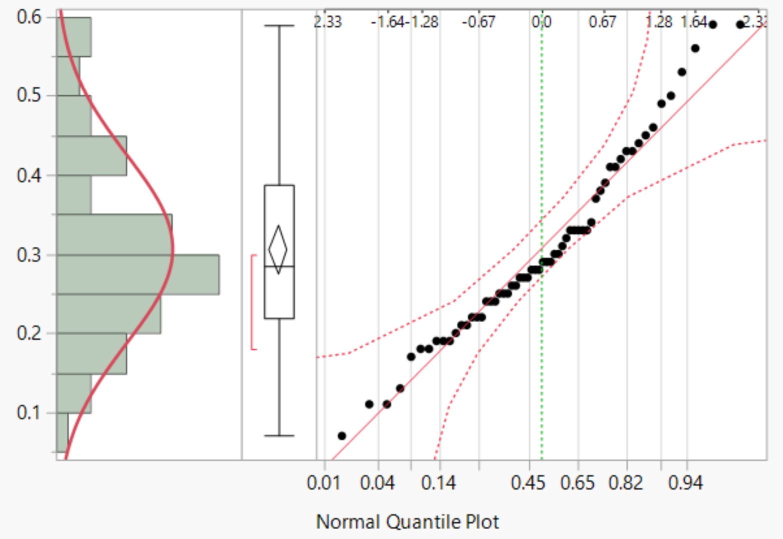
Connecting Letters Report

Level			Mean
A1 5 psi - Parallel	A		2435.2500
Nail 2		B	1687.4000
A2 5 psi - Parallel		B	1398.9500

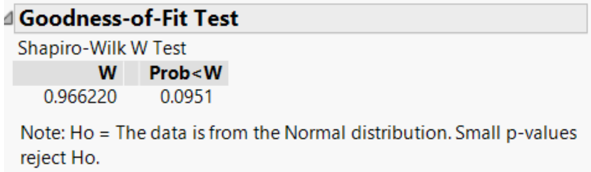
Levels not connected by same letter are significantly different.

Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit



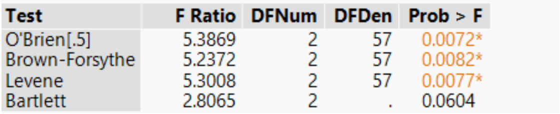
Goodness-of-Fit Test

Shapiro-Wilk W Test

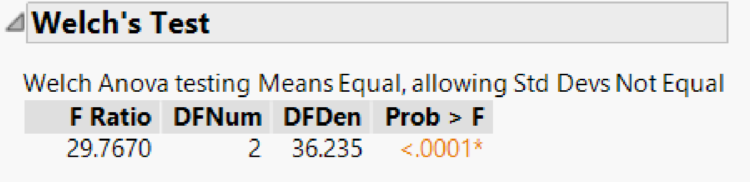
W	Prob<W
0.966220	0.0951

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



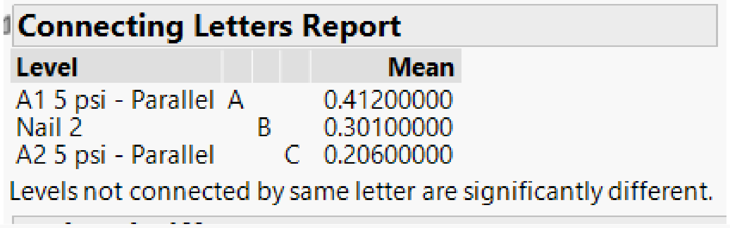
Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	5.3869	2	57	0.0072*
Brown-Forsythe	5.2372	2	57	0.0082*
Levene	5.3008	2	57	0.0077*
Bartlett	2.8065	2	.	0.0604



Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

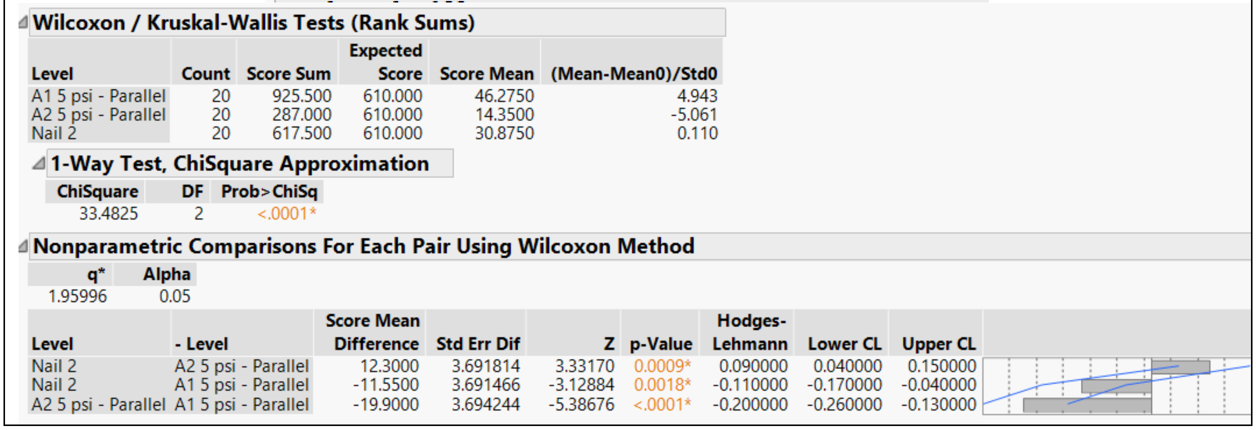
F Ratio	DFNum	DFDen	Prob > F
29.7670	2	36.235	<.0001*



Connecting Letters Report

Level				Mean
A1 5 psi - Parallel	A			0.41200000
Nail 2		B		0.30100000
A2 5 psi - Parallel			C	0.20600000

Levels not connected by same letter are significantly different.



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi - Parallel	20	925.500	610.000	46.2750	4.943
A2 5 psi - Parallel	20	287.000	610.000	14.3500	-5.061
Nail 2	20	617.500	610.000	30.8750	0.110

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
33.4825	2	<.0001*

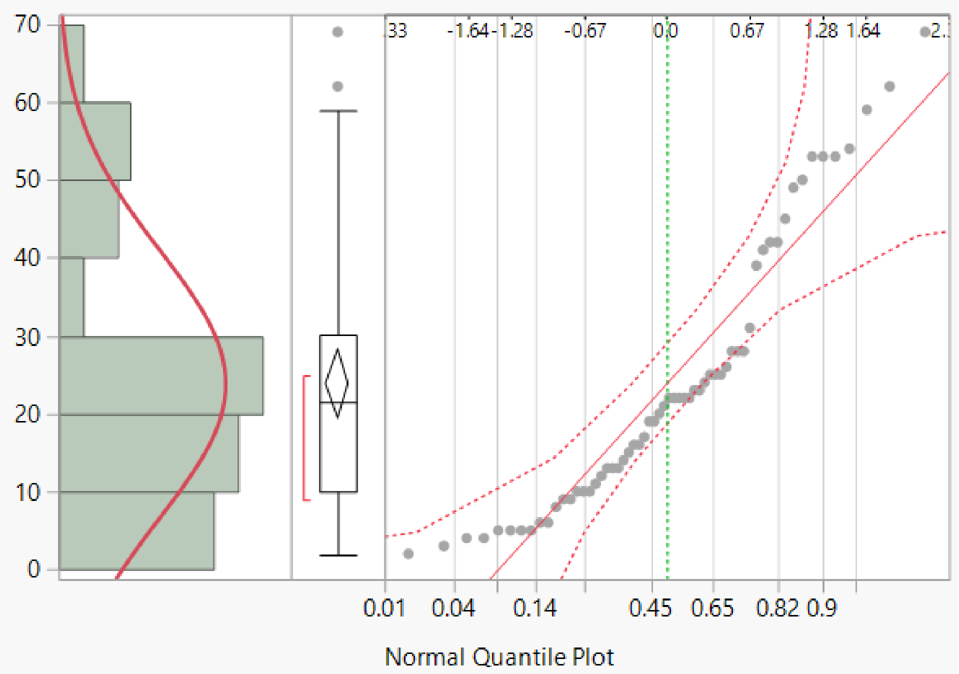
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

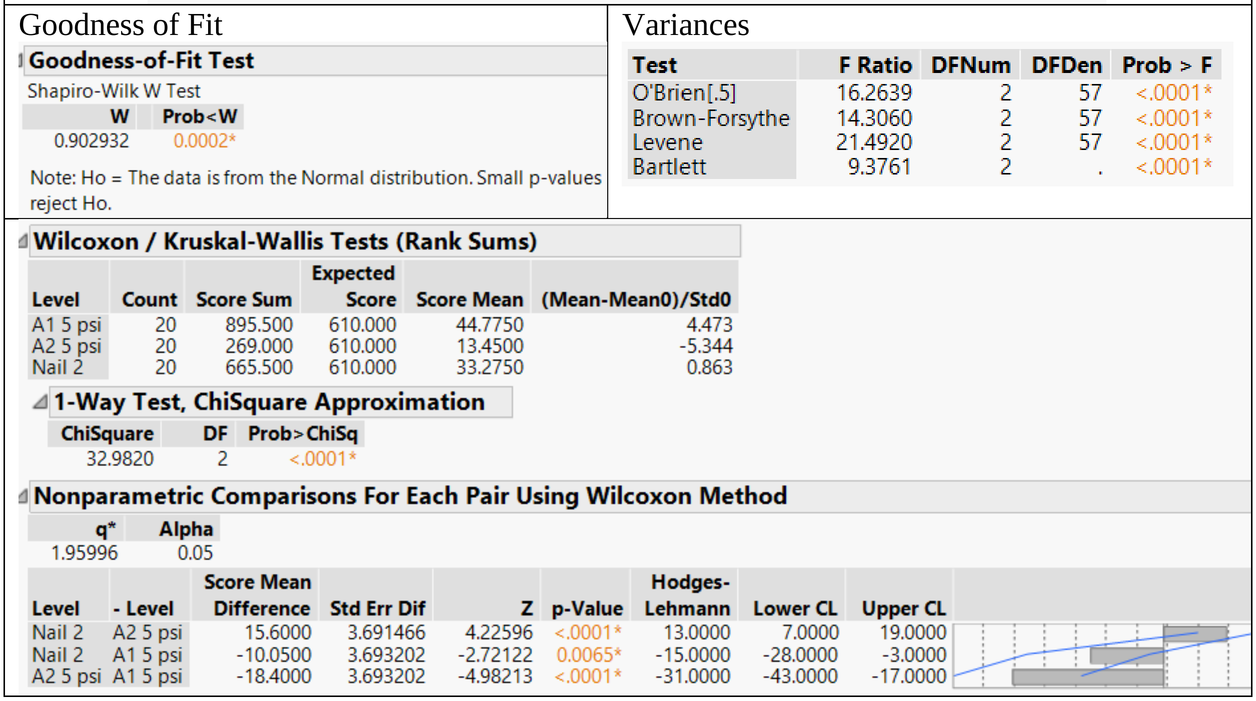
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	A2 5 psi - Parallel	12.3000	3.691814	3.33170	0.0009*	0.090000	0.040000	0.150000
Nail 2	A1 5 psi - Parallel	-11.5500	3.691466	-3.12884	0.0018*	-0.110000	-0.170000	-0.040000
A2 5 psi - Parallel	A1 5 psi - Parallel	-19.9000	3.694244	-5.38676	<.0001*	-0.200000	-0.260000	-0.130000

Energy

Distribution & Normal quantile plot





Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.902932	0.0002*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	16.2639	2	57	<.0001*
Brown-Forsythe	14.3060	2	57	<.0001*
Levene	21.4920	2	57	<.0001*
Bartlett	9.3761	2	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi	20	895.500	610.000	44.7750	4.473
A2 5 psi	20	269.000	610.000	13.4500	-5.344
Nail 2	20	665.500	610.000	33.2750	0.863

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
32.9820	2	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

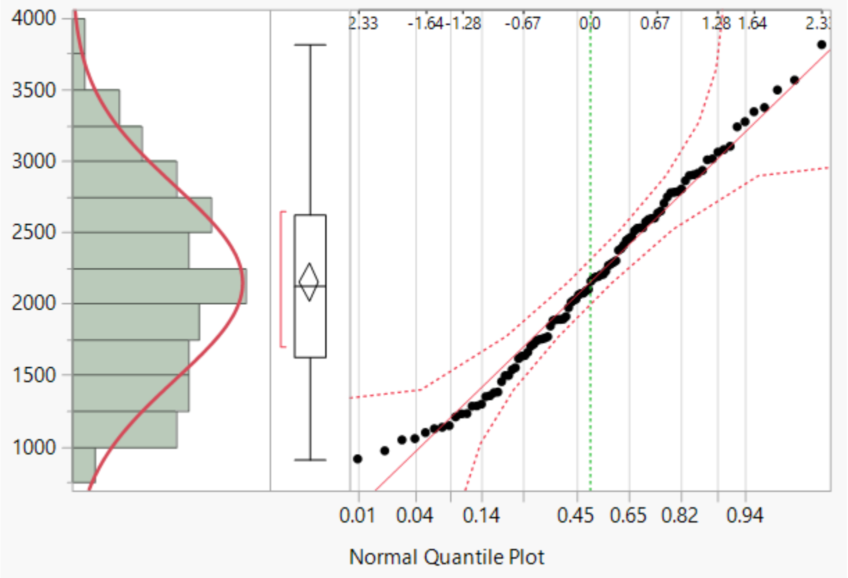
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	A2 5 psi	15.6000	3.691466	4.22596	<.0001*	13.0000	7.0000	19.0000
Nail 2	A1 5 psi	-10.0500	3.693202	-2.72122	0.0065*	-15.0000	-28.0000	-3.0000
A2 5 psi	A1 5 psi	-18.4000	3.693202	-4.98213	<.0001*	-31.0000	-43.0000	-17.0000

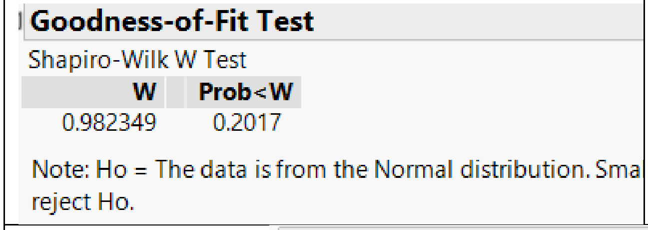
Appendix G

Load at Failure

Distribution & Normal quantile plot



Goodness of Fit



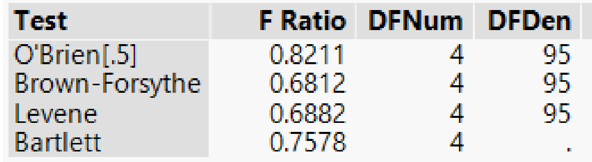
Goodness-of-Fit Test

Shapiro-Wilk W Test

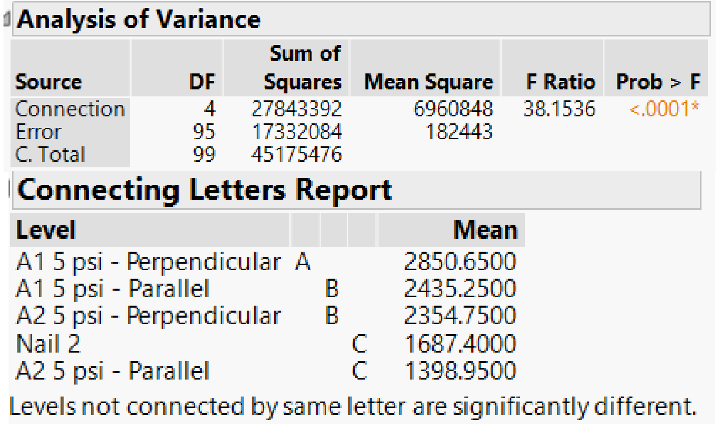
W	Prob<W
0.982349	0.2017

Note: Ho = The data is from the Normal distribution. Sma
reject Ho.

Variances



Test	F Ratio	DFNum	DFDen
O'Brien[.5]	0.8211	4	95
Brown-Forsythe	0.6812	4	95
Levene	0.6882	4	95
Bartlett	0.7578	4	.



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Connection	4	27843392	6960848	38.1536	<.0001*
Error	95	17332084	182443		
C. Total	99	45175476			

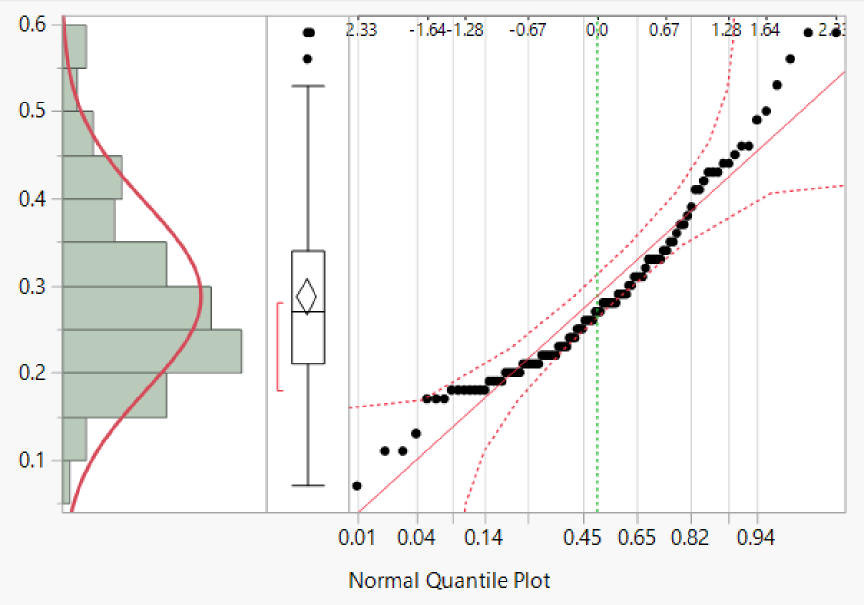
Connecting Letters Report

Level				Mean
A1 5 psi - Perpendicular	A			2850.6500
A1 5 psi - Parallel		B		2435.2500
A2 5 psi - Perpendicular		B		2354.7500
Nail 2			C	1687.4000
A2 5 psi - Parallel			C	1398.9500

Levels not connected by same letter are significantly different.

Deformation at Failure

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.943747	0.0003*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	7.1165	4	95	<.0001*
Brown-Forsythe	8.5672	4	95	<.0001*
Levene	9.0195	4	95	<.0001*
Bartlett	6.8341	4	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi - Parallel	20	1628.50	1010.00	81.4250	5.330
A1 5 psi - Perpendicular	20	1252.00	1010.00	62.6000	2.083
A2 5 psi - Parallel	20	575.500	1010.00	28.7750	-3.743
A2 5 psi - Perpendicular	20	452.500	1010.00	22.6250	-4.804
Nail 2	20	1141.50	1010.00	57.0750	1.130

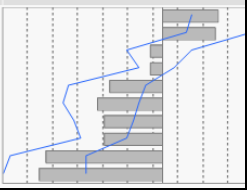
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
57.0064	4	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

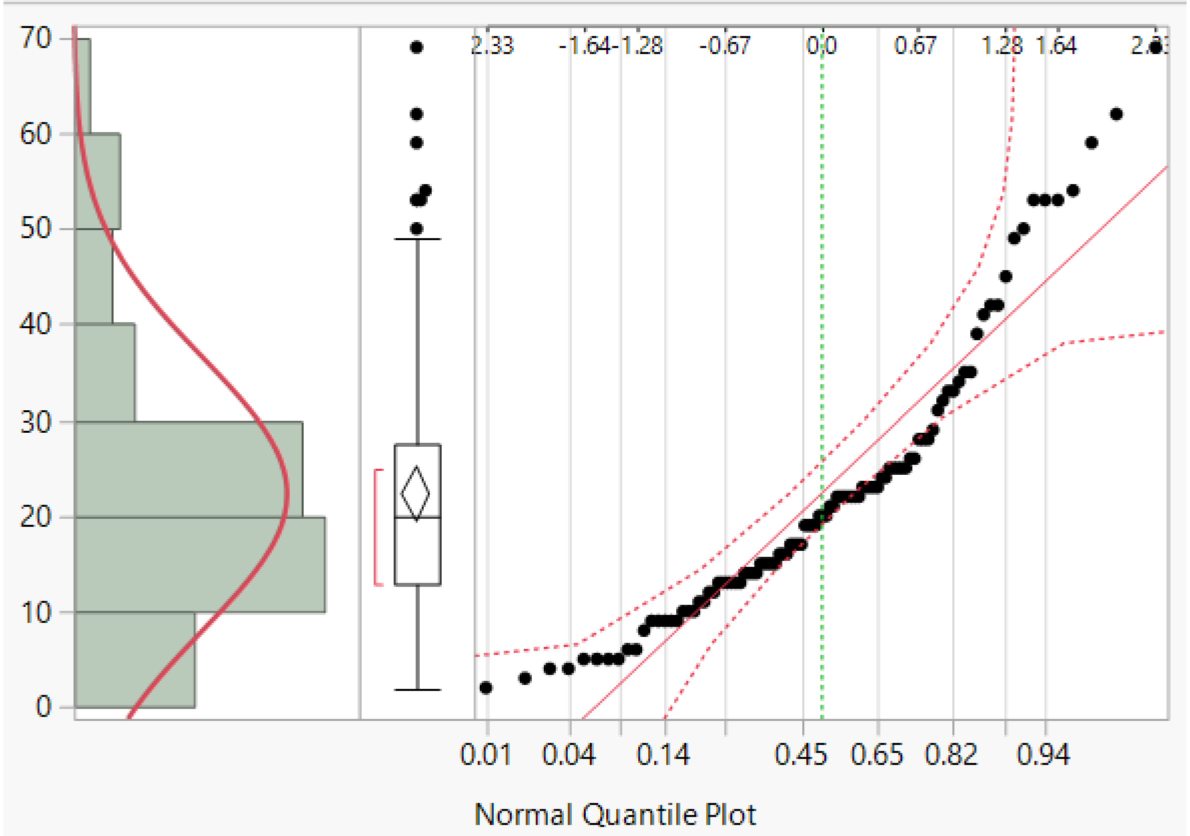
q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	A2 5 psi - Perpendicular	14.3000	3.684166	3.88148	0.0001*	0.095000	0.050000	0.150000
Nail 2	A2 5 psi - Parallel	12.3000	3.691814	3.33170	0.0009*	0.090000	0.040000	0.150000
Nail 2	A1 5 psi - Perpendicular	-1.9000	3.692161	-0.51460	0.6068	-0.020000	-0.060000	0.050000
A2 5 psi - Perpendicular	A2 5 psi - Parallel	-3.4500	3.681032	-0.93724	0.3486	-0.020000	-0.040000	0.020000
A1 5 psi - Perpendicular	A1 5 psi - Parallel	-10.3000	3.691814	-2.78996	0.0053*	-0.090000	-0.160000	-0.030000
Nail 2	A1 5 psi - Parallel	-11.5500	3.691466	-3.12884	0.0018*	-0.110000	-0.170000	-0.040000
A2 5 psi - Parallel	A1 5 psi - Perpendicular	-14.6000	3.691987	-3.95451	<.0001*	-0.100000	-0.150000	-0.050000
A2 5 psi - Perpendicular	A1 5 psi - Perpendicular	-17.9000	3.685557	-4.85680	<.0001*	-0.100000	-0.140000	-0.060000
A2 5 psi - Parallel	A1 5 psi - Parallel	-19.9000	3.694244	-5.38676	<.0001*	-0.200000	-0.260000	-0.130000
A2 5 psi - Perpendicular	A1 5 psi - Parallel	-19.9000	3.689903	-5.39310	<.0001*	-0.210000	-0.270000	-0.130000

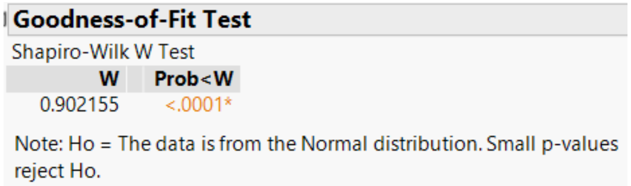


Energy

Distribution & Normal quantile plot



Goodness of Fit



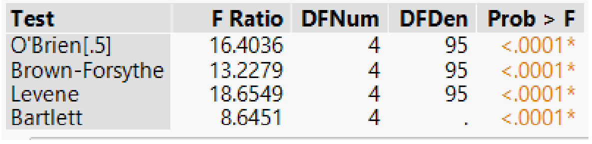
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.902155	<.0001*

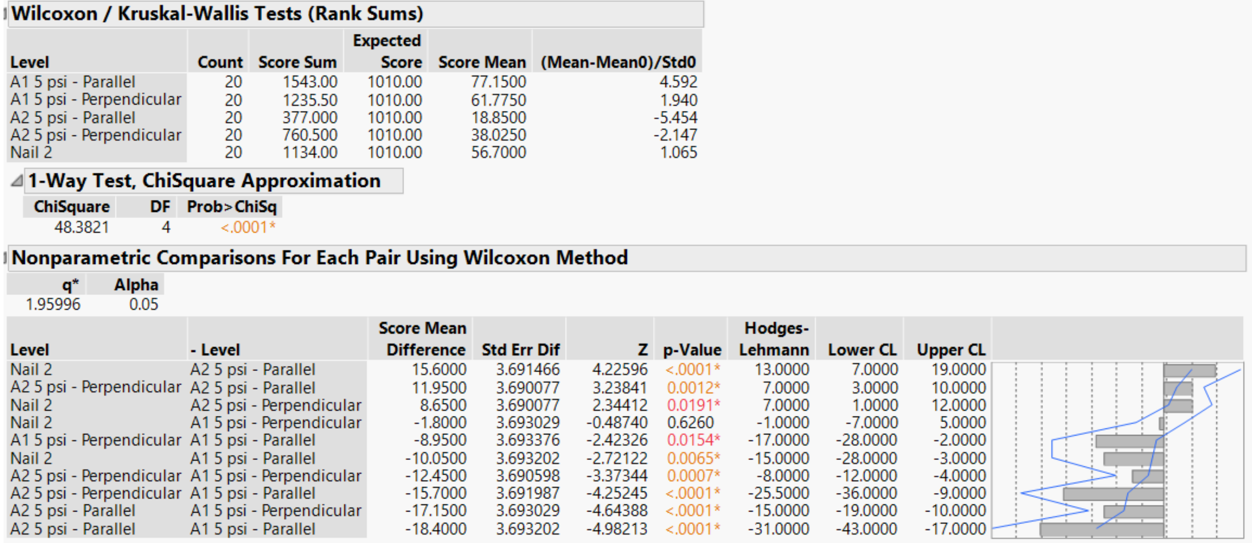
Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances



Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	16.4036	4	95	<.0001*
Brown-Forsythe	13.2279	4	95	<.0001*
Levene	18.6549	4	95	<.0001*
Bartlett	8.6451	4	.	<.0001*

Goodness of



Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi - Parallel	20	1543.00	1010.00	77.1500	4.592
A1 5 psi - Perpendicular	20	1235.50	1010.00	61.7750	1.940
A2 5 psi - Parallel	20	377.000	1010.00	18.8500	-5.454
A2 5 psi - Perpendicular	20	760.500	1010.00	38.0250	-2.147
Nail 2	20	1134.00	1010.00	56.7000	1.065

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
48.3821	4	<.0001*

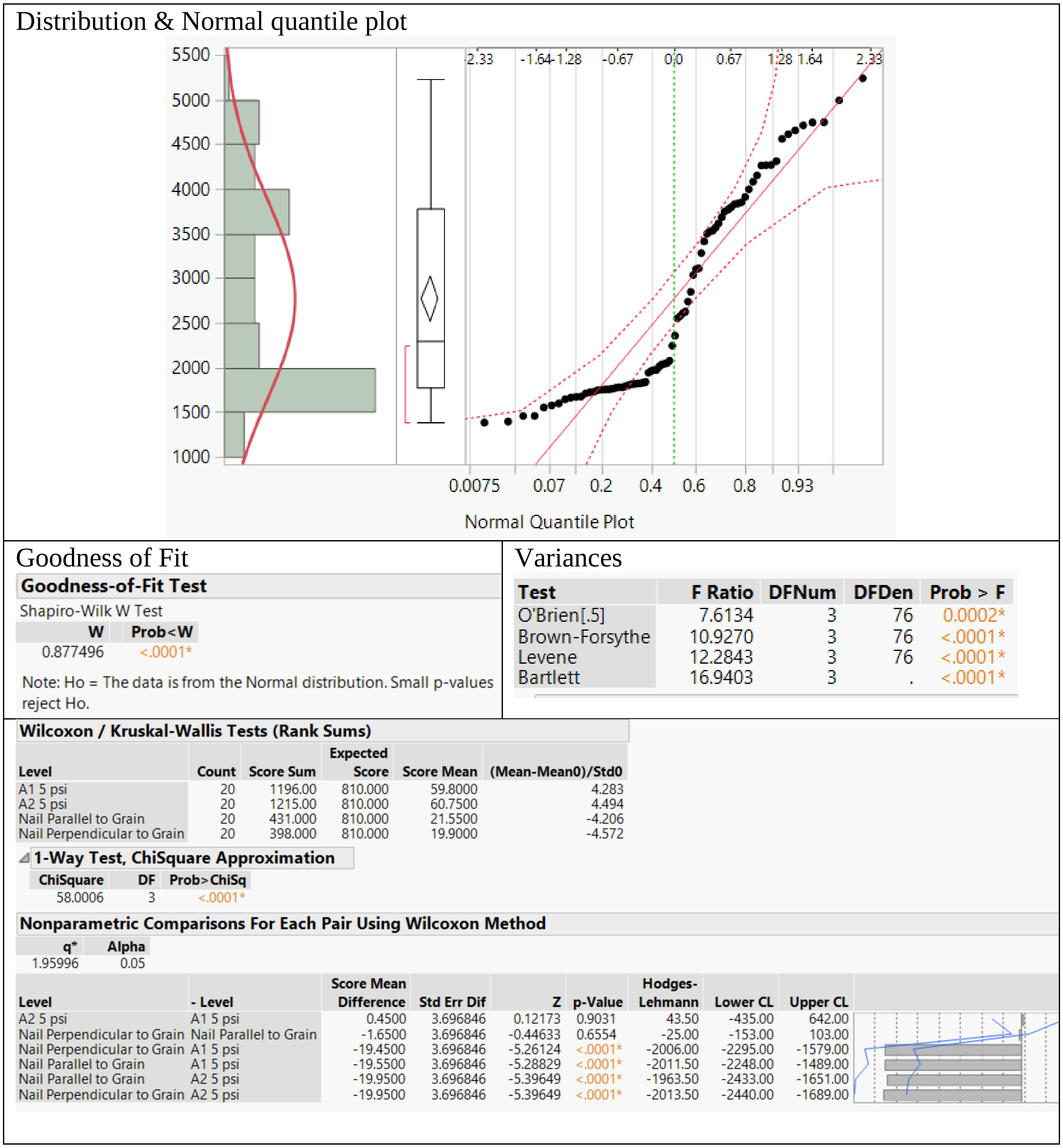
Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail 2	A2 5 psi - Parallel	15.6000	3.691466	4.22596	<.0001*	13.0000	7.0000	19.0000
A2 5 psi - Perpendicular	A2 5 psi - Parallel	11.9500	3.690077	3.23841	0.0012*	7.0000	3.0000	10.0000
Nail 2	A2 5 psi - Perpendicular	8.6500	3.690077	2.34412	0.0191*	7.0000	1.0000	12.0000
Nail 2	A1 5 psi - Perpendicular	-1.8000	3.693029	-0.48740	0.6260	-1.0000	-7.0000	5.0000
A1 5 psi - Perpendicular	A1 5 psi - Parallel	-8.9500	3.693376	-2.42326	0.0154*	-17.0000	-28.0000	-2.0000
Nail 2	A1 5 psi - Parallel	-10.0500	3.693202	-2.72122	0.0065*	-15.0000	-28.0000	-3.0000
A2 5 psi - Perpendicular	A1 5 psi - Perpendicular	-12.4500	3.690598	-3.37344	0.0007*	-8.0000	-12.0000	-4.0000
A2 5 psi - Perpendicular	A1 5 psi - Parallel	-15.7000	3.691987	-4.25245	<.0001*	-25.5000	-36.0000	-9.0000
A2 5 psi - Parallel	A1 5 psi - Perpendicular	-17.1500	3.693029	-4.64388	<.0001*	-15.0000	-19.0000	-10.0000
A2 5 psi - Parallel	A1 5 psi - Parallel	-18.4000	3.693202	-4.98213	<.0001*	-31.0000	-43.0000	-17.0000

5.7 Appendix G – Statistics for the effect of connection method on the shear strength of the connection

Load at Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.877496	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	7.6134	3	76	0.0002*
Brown-Forsythe	10.9270	3	76	<.0001*
Levene	12.2843	3	76	<.0001*
Bartlett	16.9403	3	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi	20	1196.00	810.000	59.8000	4.283
A2 5 psi	20	1215.00	810.000	60.7500	4.494
Nail Parallel to Grain	20	431.000	810.000	21.5500	-4.206
Nail Perpendicular to Grain	20	398.000	810.000	19.9000	-4.572

1-Way Test, ChiSquare Approximation

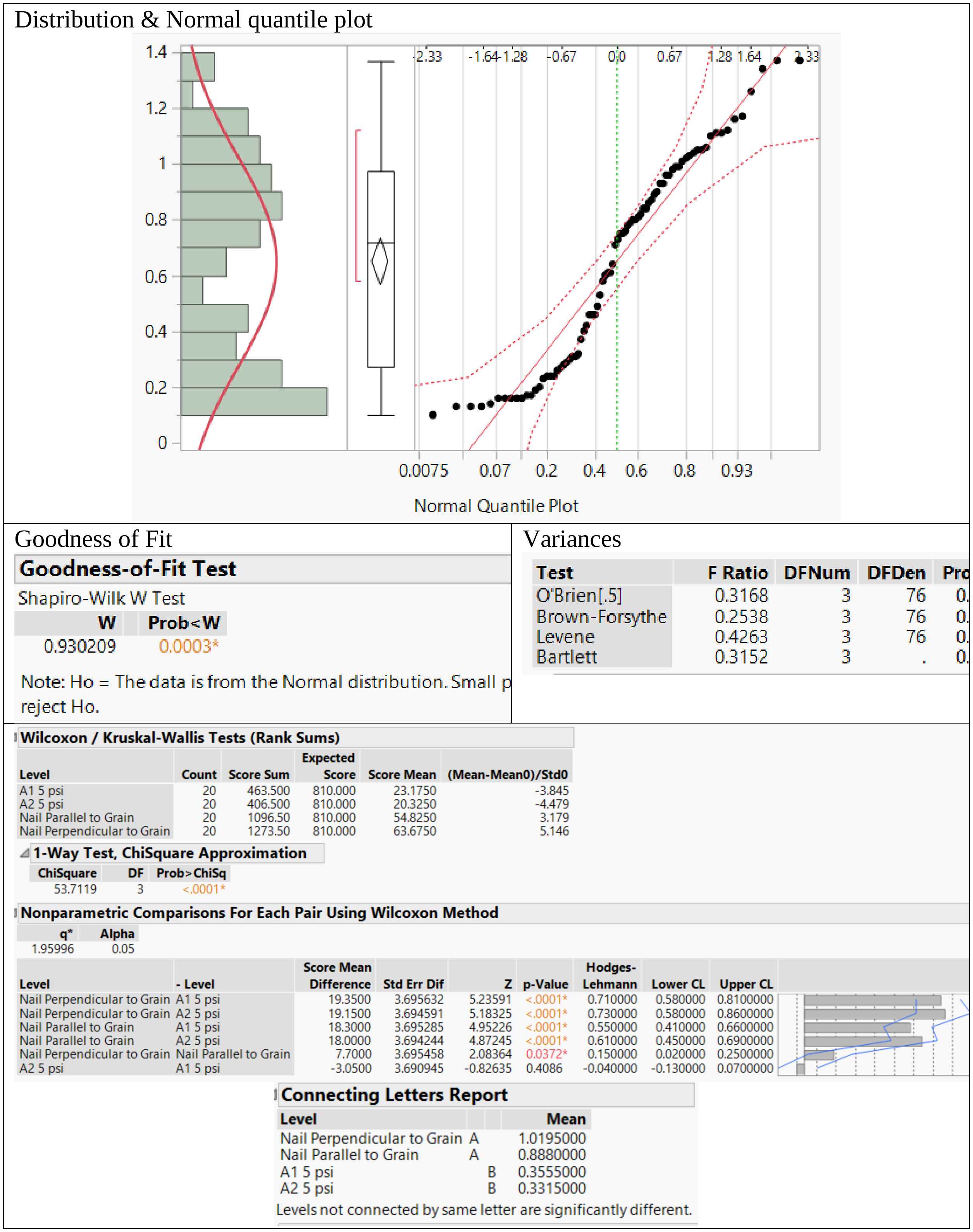
ChiSquare	DF	Prob>ChiSq
58.0006	3	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
A2 5 psi	A1 5 psi	0.4500	3.696846	0.12173	0.9031	43.50	-435.00	642.00
Nail Perpendicular to Grain	Nail Parallel to Grain	-1.6500	3.696846	-0.44633	0.6554	-25.00	-153.00	103.00
Nail Perpendicular to Grain	A1 5 psi	-19.4500	3.696846	-5.26124	<.0001*	-2006.00	-2295.00	-1579.00
Nail Parallel to Grain	A1 5 psi	-19.5500	3.696846	-5.28829	<.0001*	-2011.50	-2248.00	-1489.00
Nail Parallel to Grain	A2 5 psi	-19.9500	3.696846	-5.39649	<.0001*	-1963.50	-2433.00	-1651.00
Nail Perpendicular to Grain	A2 5 psi	-19.9500	3.696846	-5.39649	<.0001*	-2013.50	-2440.00	-1689.00

Deformation at Failure



Distribution & Normal quantile plot

Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.930209	0.0003*

Note: Ho = The data is from the Normal distribution. Small p reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Pro
O'Brien[.5]	0.3168	3	76	0.
Brown-Forsythe	0.2538	3	76	0.
Levene	0.4263	3	76	0.
Bartlett	0.3152	3	.	0.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi	20	463.500	810.000	23.1750	-3.845
A2 5 psi	20	406.500	810.000	20.3250	-4.479
Nail Parallel to Grain	20	1096.50	810.000	54.8250	3.179
Nail Perpendicular to Grain	20	1273.50	810.000	63.6750	5.146

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
53.7119	3	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail Perpendicular to Grain	A1 5 psi	19.3500	3.695632	5.23591	<.0001*	0.710000	0.580000	0.8100000
Nail Perpendicular to Grain	A2 5 psi	19.1500	3.694591	5.18325	<.0001*	0.730000	0.580000	0.8600000
Nail Parallel to Grain	A1 5 psi	18.3000	3.695285	4.95226	<.0001*	0.550000	0.410000	0.6600000
Nail Parallel to Grain	A2 5 psi	18.0000	3.694244	4.87245	<.0001*	0.610000	0.450000	0.6900000
Nail Perpendicular to Grain	Nail Parallel to Grain	7.7000	3.695458	2.08364	0.0372*	0.150000	0.020000	0.2500000
A2 5 psi	A1 5 psi	-3.0500	3.690945	-0.82635	0.4086	-0.040000	-0.130000	0.0700000

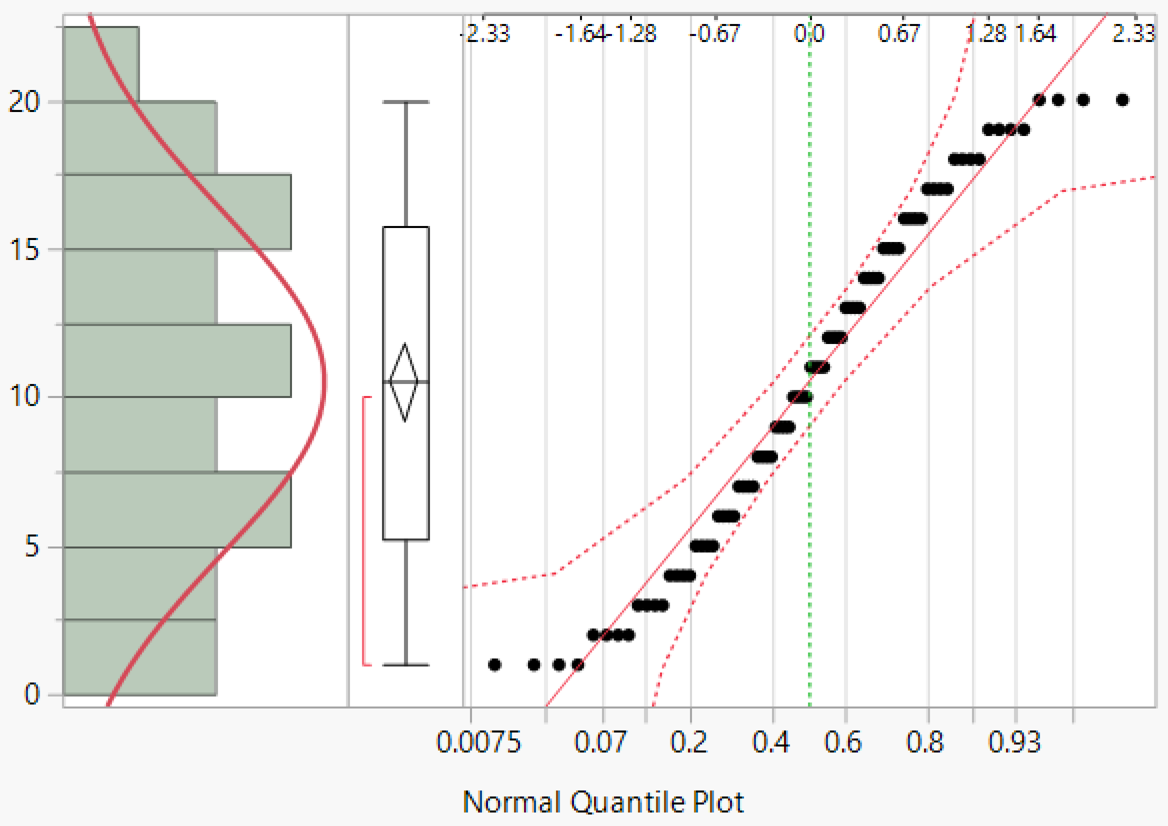
Connecting Letters Report

Level			Mean
Nail Perpendicular to Grain	A		1.0195000
Nail Parallel to Grain	A		0.8880000
A1 5 psi		B	0.3555000
A2 5 psi		B	0.3315000

Levels not connected by same letter are significantly different.

Energy

Distribution & Normal quantile plot



Goodness of Fit

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.949538	0.0032*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	4.0498	3	76	0.0100*
Brown-Forsythe	5.7067	3	76	0.0014*
Levene	10.9933	3	76	<.0001*
Bartlett	18.9725	3	.	<.0001*

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
A1 5 psi	20	719.500	810.000	35.9750	-1.000
A2 5 psi	20	666.500	810.000	33.3250	-1.589
Nail Parallel to Grain	20	736.000	810.000	36.8000	-0.817
Nail Perpendicular to Grain	20	1118.00	810.000	55.9000	3.417

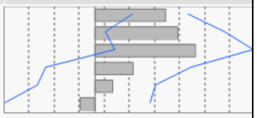
1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
11.9597	3	0.0075*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Nail Perpendicular to Grain	Nail Parallel to Grain	14.2000	3.694938	3.84310	0.0001*	28.0000	15.0000	37.00000
Nail Perpendicular to Grain	A1 5 psi	8.4500	3.695632	2.28648	0.0222*	33.0000	4.0000	52.00000
Nail Perpendicular to Grain	A2 5 psi	8.0000	3.696152	2.16441	0.0304*	40.0000	8.0000	63.00000
Nail Parallel to Grain	A2 5 psi	4.4000	3.695458	1.19065	0.2338	15.0000	-20.0000	38.00000
Nail Parallel to Grain	A1 5 psi	2.3500	3.695111	0.63598	0.5248	7.0000	-23.0000	24.00000
A2 5 psi	A1 5 psi	-1.8000	3.695285	-0.48711	0.6262	-6.0000	-36.0000	22.00000



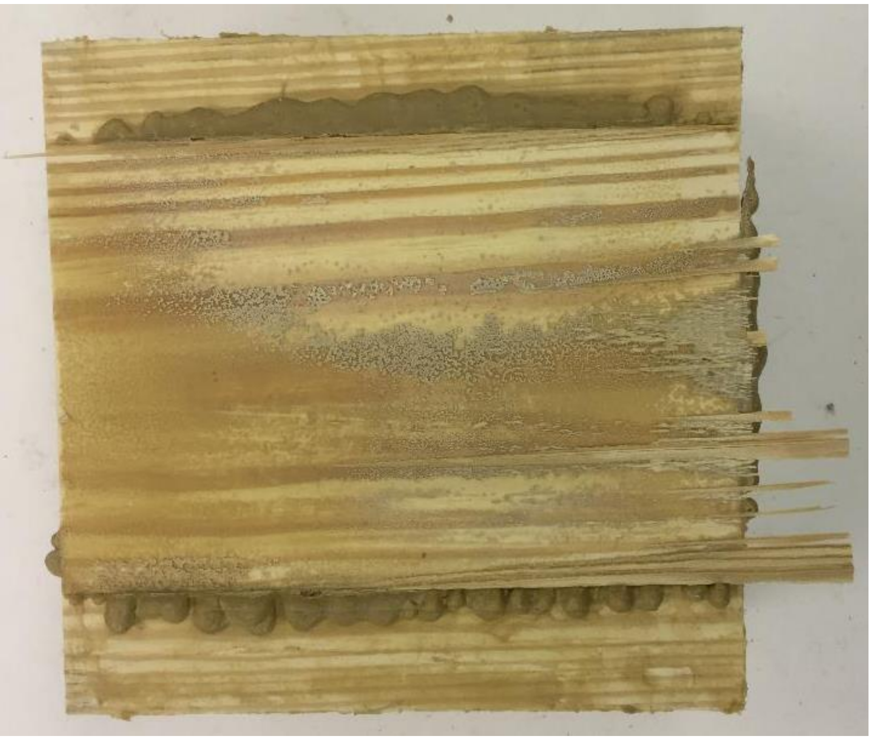
5.8 Appendix H – Images of failure after testing

Low amounts of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in tension perpendicular to the grain

High amounts of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in tension perpendicular to the grain

Low amounts of wood failure for samples made with the emulsion polymer isocyanate (EPI) and tested in tension perpendicular to the grain

High amounts of wood failure made with the emulsion polymer isocyanate (EPI) and tested in tension perpendicular to the grain



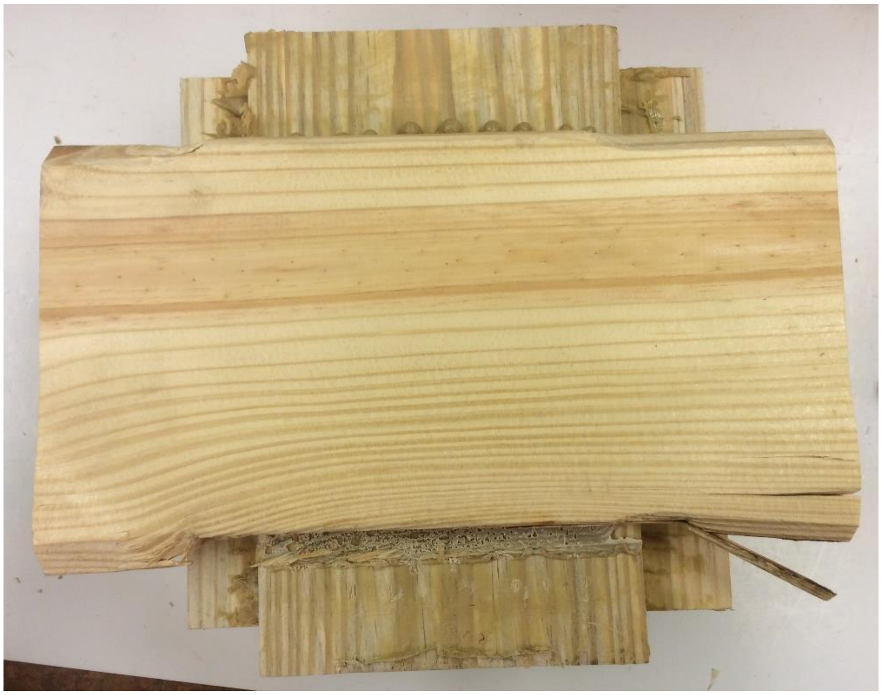
Low amounts of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in tension parallel to the grain

High amounts of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in tension parallel to the grain

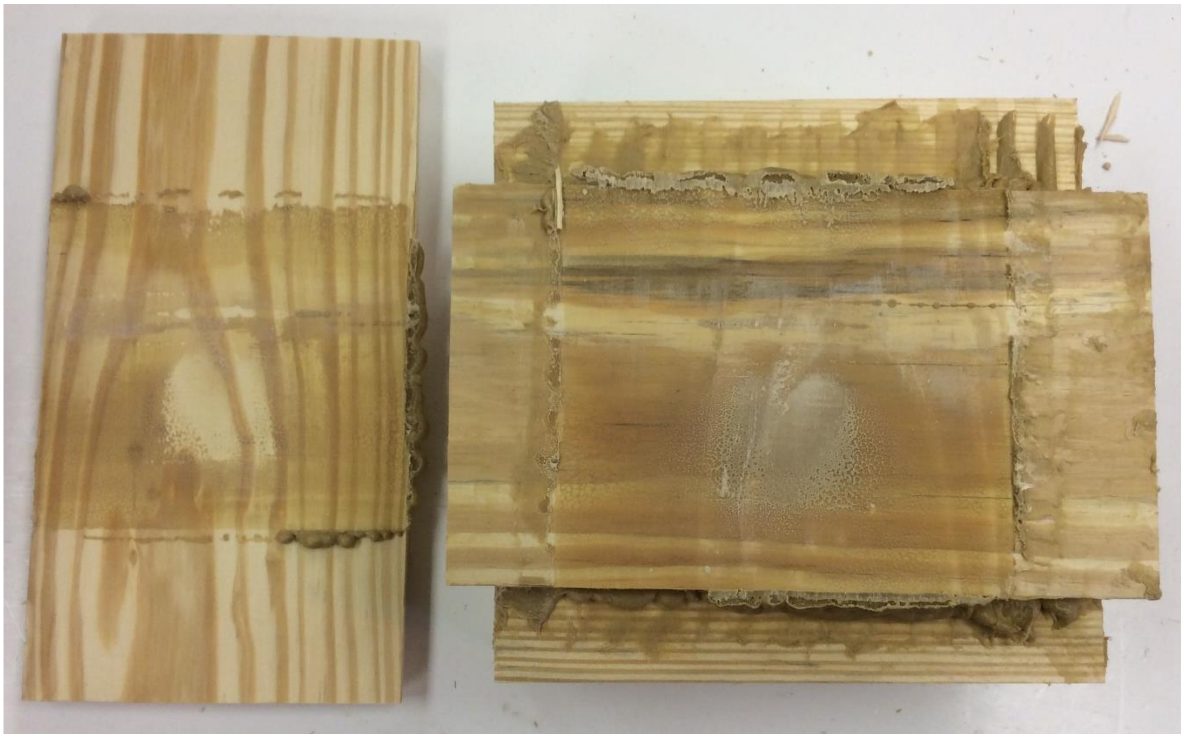
Low amounts of wood failure made with the emulsion polymer isocyanate (EPI) and tested in tension parallel to the grain

High amounts of wood failure made with the emulsion polymer isocyanate (EPI) and tested in tension parallel to the grain

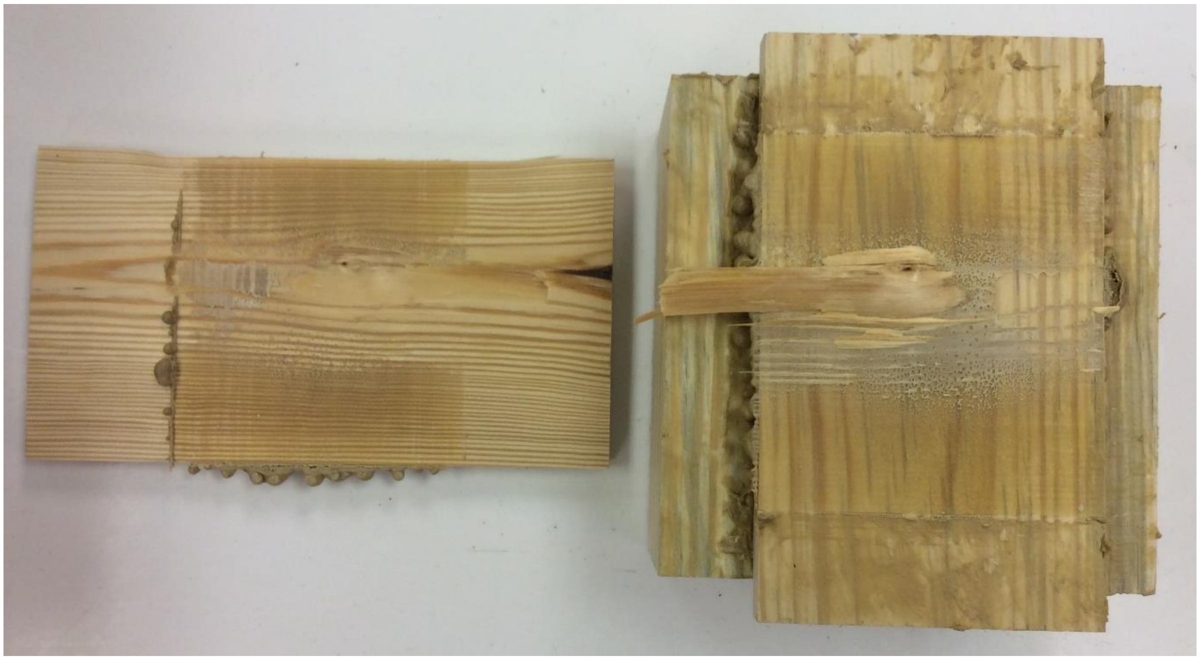
Lower amount of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in shear with compression failure



Higher amount of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in shear with compression failure



Low amount of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in shear with shear failure



Higher amount of wood failure for samples made with the solvent based construction adhesive (SBCA) and tested in shear with shear failure

Wood failure for samples made with the emulsion polymer isocyanate (EPI) and tested in shear with compression failure

Low amount of wood failure for samples made with the emulsion polymer isocyanate (EPI) and tested in shear with shear failure

High amount of wood failure for samples made with the emulsion polymer isocyanate (EPI) and tested in shear with shear failure

Side view of withdrawal failure of nailed samples tested in tension

Top view of withdrawal failure of nailed samples tested in tension

Side view of failure of nailed samples tested in shear

Top view of failure of nailed samples tested in shear