

Predicting the Joint Stiffness of Wooden Pallets Assembled with Lag Screws and Carriage Bolts

Joseph David Keller

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Laszlo Horvath, Committee Chair

Joseph Loferski

Eduardo Molina

John Bouldin

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ABSTRACT

Wood is the most commonly used pallet material in the US with a 95% market share. To design pallets that can be used safely, the load capacity of the pallet needs to be measured or calculated. Although the load capacity of a pallet depends on a multitude of factors, the stiffness of the joints between pallet components has a major influence on overall pallet load capacity. While the strength values of different fastener types are well documented, the stiffness values of pallet joints have not been studied to the same level. In 1989, a research study was performed to predict the rotational stiffness of pallet joints constructed using common pallet nails. Although these common pallet nails are ubiquitous in the industry, heavy-duty pallets are often assembled with alternative fasteners such as bolts and lag screws.

Currently, the effect of these alternative fasteners on joint stiffness is not understood; this limits the use of these fasteners by the industry. Therefore, the objective of this research was to investigate the stiffness of pallet joints constructed using alternative fasteners such as bolts and lag screws. In order to predict joint stiffness, head embedment stiffness, shank withdrawal stiffness, and rotational stiffness were measured for each joint type. It was found that head embedment, shank withdrawal and edge crushing stiffnesses were all significantly greater for alternative fasteners than for common pallet nails. We've concluded that the model that had been developed for common pallet nails cannot be used to predict the performance of pallet joints made with alternative fasteners. The results of this study will be included in the Pallet Design System (PDS) software in order to allow pallet designers to design pallets using bolts and lag screws.

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GENERAL AUDIENCE ABSTRACT

Pallets are used all over the world in the field of distribution. The strength values associated with a pallet have been thoroughly investigated by many different researchers; however, the stiffness values associated with pallet joints have not. The goal of this work was to investigate the stiffnesses associated with pallets joints made with lag screws and carriage bolts. It is important to understand that different materials, fastening methods, and design considerations can have a huge impact on the stiffness of the joint. This paper will discuss the various tests that were used to measure the actual stiffness of pallet joints and the results of those tests. Afterwards, the researchers detail their attempt to predict the stiffness using an equation created from the actual test data. Finally, by understanding the effects of these various factors, better pallet designs can be created that are both safer and stronger using the investigated alternative fasteners.

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1. LITERATURE REVIEW

1.1 Pallet History

Distribution is one of the largest industries in the world, and it has a storied past. Humans have always had the need to transport goods from one place to another. The main way that this need has been fulfilled throughout history has been by using platforms on which people can store their goods. Originally these platforms were called skids; the skid was upgraded in 1926 with the addition of bottom deck boards. This platform then became known as a pallet (LeBlanc, 2002). Pallets are the main way on which goods are shipped today. The modern pallet rose in popularity because of an invention which made distribution by pallet very practical, the forklift. Forklifts started being used in 1887 and were improved during the 1900s (LeBlanc, 2002). Forklifts have been improved over time to incorporate elements like motors, hydraulic controls, and most-importantly a cantilevered fork design (LeBlanc, 2002). It was the cantilever fork design that led to what we currently use as a pallet. Because of this invention, it became easier for large loads to be lifted and shipped, and these large loads were shipped on the easiest base for the new forklifts to pick up, which was a pallet. A large increase in the use of pallets was seen during World War II when forklifts and pallets were used to quickly ship supplies to battlefields (LeBlanc, 2018). Once the war was over, the use of pallets became more commercial. Companies began to store their products on pallets, and this new “unit load” became the main method of distribution. Pallets have become a staple in the commercial distribution system. Today around 80% of U.S. trade is moved via pallets (Raballan, G. and Aldaz-Carroll, E. 2005).

1.2 Pallet Market

The driving force setting the prices in the pallet market is the lumber industry. This is due to the fact that the majority of pallets used by the industry are wooden; 95% of pallets used by companies are manufactured from wood (McCrea, 2022). Many of these are single-use pallets created with new lumber. In 2016, 508 million new wood

pallets were produced in the U.S. by various companies in the pallet market. This was an increase of 22% compared to 2011 when it was estimated only 416 million new pallets were produced that year (Gerber et al., 2020). Since 2011, 326 million pallets were remanufactured or recycled and have remained in circulation (Gerber et al., 2020). Wooden pallets can be reused. They are separated and graded based on what kind of repairs have had to be made to the pallet. At Municipal Solid Waste or MSW facilities, specifically, 13.8 million pallets were reused or repurposed. At these same facilities, 18.3 million pallets were landfilled. A group of Construction and Demolition or C&D facilities saw 38.3 million pallets reused as well as 19.2 million pallets put in landfills (Shiner et al., 2021). Repairing and recycling pallet parts can be very beneficial to companies and save them a lot of money. There are many uses for pallets after they are no longer able to be used in the distribution chain. One of the uses includes turning pallet wood into mulch or animal bedding. Another use is breaking the pallet down into fiber-based products or biofuel (Gerber et al. 2020). The lifecycle of a pallet has many different paths along which it can branch off, but each one can be profitable for different industries beyond packaging and distribution.

1.3 Materials

1.3.1 Wood

The most common material used to manufacture pallets is solid wood. Many different types of wood species can be used depending on what type of lumber is available in the location where the pallet is being manufactured (**Figure 1**). There are two different types of lumber, hardwood and softwood, each of which has unique properties when used in pallet construction. Hardwood lumber contains, ray cells, vessels, and fibers. In comparison, softwood lumber predominantly made of tracheid cells, and some types of softwoods also include resin canals. Hardwood pallets tend to be more durable, and they can hold more weight because hardwoods are denser than softwoods. The density of the wood is important because denser wood retains its shape better. Softwood pallets can offer better affordability, and they can also have lower repair costs, but the performance and longevity of hardwood pallets are typically better. Most operations and applications can be served well by softwood pallets which are more popular than

hardwood pallets in the industry. In 2006, 30%-36% of hardwood lumber produced in the United States was used for pallet production (Gerber et al. 2020). In the same year, the pallet industry only used 5.6% of U.S.-produced softwood lumber (Gerber et al, 2020).



Figure 1: Wood species common to each region of the United States (adapted from Park 2015).

Commonly, pallets are created using low-grade lumber left over from the construction industry (Bejune, 2001). Pallets are commonly constructed using “two-by-fours” which are 1.5-inch, by 3.5-inch lumber. These boards are what are standardly used for building construction. Wooden pallets have benefits compared to other pallet materials. The cost-to-performance ratio of wooden pallets is the best among common pallet materials (Clarke, 2004). Wooden pallets do have some disadvantages compared to other pallet materials. The fasteners used to hold wooden pallets together can damage products. Another disadvantage are the pests which can hide in wooden pallets and cause issues during distribution (Clarke, 2004). Mold or other fungi can be spread on wooden pallets if not properly treated. Wooden pallets need to be properly conditioned and maintained so that issues do not arise.

1.3.2 Plastic

There are many different types of plastic pallets in circulation, but the two most common are high-density polyethylene (HDPE), and polypropylene (PP). Plastic pallets are utilized by 31% of companies in today's marketplace, however that number is down from 2020 when 31% of companies were using plastic pallets (McCrea, 2022). Plastic pallets are favored over wood pallets by some companies because they are generally lighter weight, and they resist moisture very well. The moisture resistance of plastic makes these pallets common in food distribution systems. However, one major disadvantage of these pallets is that each type of plastic pallet can be up to six times the price when compared to a wooden pallet (Clarke 2004). Plastic pallets are most commonly reusable, and can be used for many repeated trips, whereas wooden pallets are more commonly single use.

1.3.3 Composite

Composite pallets can be made up of materials such as OSB or plywood which are wood bonded with external adhesive (which is fully waterproof) (NWPCA, 2014). These types of pallets make up a smaller market share because of their current high price compared to solid wood pallets, and their high variability (McCrea, 2022). However, these types of pallets are generally less expensive than plastic pallets which can be useful. The number of trips these pallets can sustain are less than plastic pallets generally, so they are situational.

1.3.4 Paper Based Pallets

Paper pallets only used by 4% of companies and includes materials such as fiberboard, corrugated, and honeycomb (McCrea, 2022). Paper-based pallets are lightweight and are usually single-use pallets that are very easy to recycle. However, in terms of cost, they are more expensive to produce than wooden pallets. These types of pallets are also very susceptible to moisture and have low durability compared to other pallet types.

1.3.5 Metal Based Pallets

Metal pallets are mainly manufactured from steel and aluminum, and these types of pallets are only used by 6% of the industry because of their high price. Metal pallets do have amazing load capacity and very high strength and stiffness (McCrea, 2022). Another major positive of metal pallets is their recyclability. Metal pallets can be easily recycled at the proper facilities. However, metal pallets are very expensive, and they are heavier than other pallet types. For military use or other heavy duty industrial needs, the increased strength provided by metal pallets can be beneficial.

1.4 Classifications

Pallet classification can be separated into two main design categories: stringer pallets and block pallets. These two differing designs make up most of the inventory of pallets used in the industry today. Both stringer and block pallets are made up of top and bottom deck boards with fasteners attaching these boards to their middle components. These middle components are where the two types of pallets differ; stringer pallets have stringers between the top and bottom deck boards, while block pallets consist of a series of blocks connected with stringer boards between the deck boards (ANSI MH1 Committee, 2021).

1.4.1 Stringer Pallets

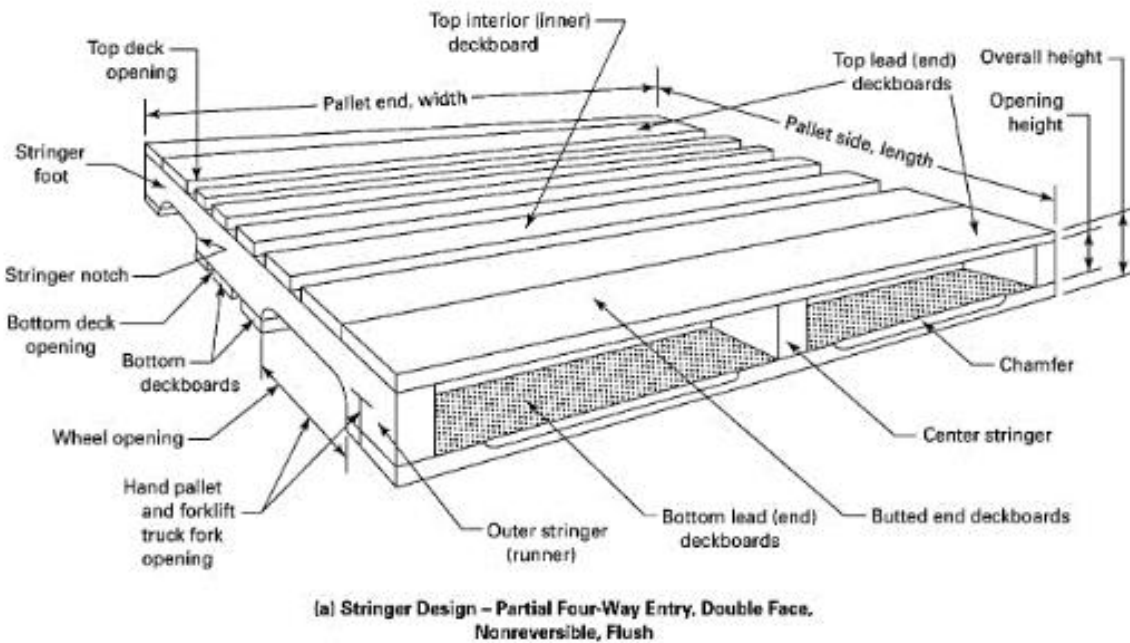


Figure 2: Construction and components of a stringer pallet type (adapted from: ANSI MH1 Committee, 2021)

Stringer pallets consist of at least two, but more commonly three, stringers (Figure 2). These stringers typically have notches in them to allow forklifts access to the length sides of the stringer pallet; however, there are stringers made of solid wood (ANSI MH1 Committee, 2021).

1.4.2 Block Pallets

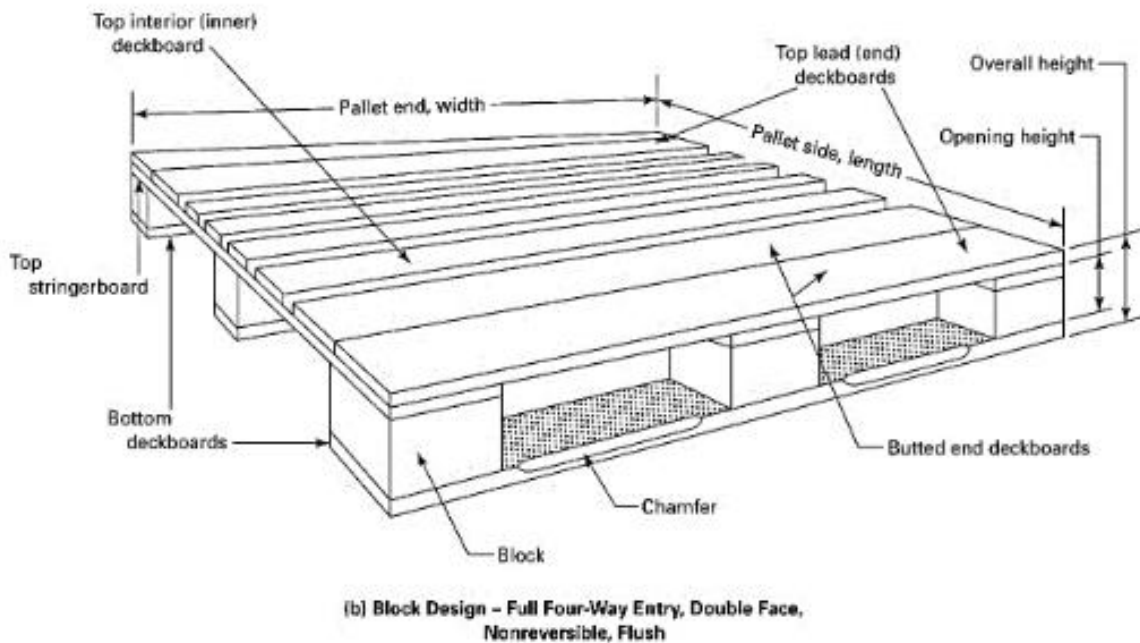


Figure 3: Construction and components of a block pallet (adapted from: ANSI MH1 Committee, 2021)

Block pallets consist of a series of blocks connected with stringer boards (**Figure 3**), typically ranging from six to nine, which are used as spacers between the top and bottom deck boards and allow access by common handling equipment. These blocks can vary in size and thickness depending on the sizes of the top and bottom deckboards to which they are fastened (ANSI MH1 Committee, 2021).

1.4.3 Entry Types

The number of ways that a pallet can be accessed are differentiated. The first entry type is the two-way entry pallet which means the pallet can only be accessed on two of its ends. An example of this type would be an unnotched stringer pallet. The second entry type is the partial four-way entry pallet which has access points on all sides, but two have limited accessibility that can only be used for handling equipment like pallet jacks. Notched stringer pallets are the most commonly used type of partial four-way pallets. Lastly, is the full four-way entry pallet. These pallets have access points from all

orientations, and they can be handled by all standard handling equipment. Block pallets are examples of full four-way pallets (NWPCA, 2014).

1.4.4 Styles

Pallets can be categorized into three different styles. Pallets can be single-face, double-face nonreversible, and double-face reversible (NWPCA, 2014). Single-face pallets only have a top deck. A good example of this is a skid. Double-faced, nonreversible pallets have both a top and bottom deck, but this type of pallet has distinct decks meaning the top and bottom decks are unique and cannot be interchanged. Double-faced, reversible pallets are versatile. The top and bottom decks on these types of pallets can be interchanged, the top deck can become the bottom deck and vice-versa.

1.4.5 Wing Pallets

Top or bottom deckboard construction can vary based on the positions of both the top and the bottom deckboards relative to the middle blocks or stringers. If a pallet has stringers whose ends are in line with the top and bottom deckboards, the pallet is considered flush. In comparison, winged pallets are ones where the top deckboards of the pallet hang over the stringers. Finally, a double-winged pallet has both the top and bottom deckboards overhanging the stringers. Block pallets are almost always flush (ANSI MH1 Committee, 2021).

1.4.6 Bottom Deck Constructions

The construction of the bottom deck boards on pallets has four main types: unidirectional bottom deck boards, perimeter bottom deck boards, overlapping bottom deck boards, and cruciform bottom deck boards (NWPCA, 2014). Unidirectional bottom deck boards are oriented in one direction: length or width. Perimeter bottom deck boards are oriented in both the length direction and the width direction. Cruciform bottom deck boards are cross-shaped and similar to the perimeter bottom deck boards in that the boards are oriented in both the length and width directions, but cruciform bottom deck boards contain connector boards, end boards, and butted boards, or can have panels with cutouts. Lastly overlapping bottom deck boards are oriented in both the length and the width directions and contain both bottom deckboards and bottom stringerboards (NWPCA 2014).

1.4.7 Sizes

Pallets come in a variety of sizes depending on the region from which the pallet originates and for which industry the pallet is being used. The lengths of pallets are defined as the length which is parallel to the stringer boards in a block pallet, and the length which is parallel to the stringers in a stringer pallet. The pallet width is the dimension oriented perpendicular to the length dimension of the pallet (ASTI MH1 Committee, 2021). In the United States, the most commonly manufactured pallet size is 48 in. x 40 in. for the length and width respectively (Gerber et al., 2020). Around the world, pallet sizes vary based on how the distribution systems in different countries are optimized (**Table 1**). In the United States, warehouses are optimized for 48 in. x 40 in. pallets, while in Europe, 47.24 in. x 39.37 in. (or 1200 mm x 1000 mm) pallets are the most common. Companies in Europe optimize their warehouses based on that size.

Table 1: Pallet sizes in millimeters and inches from around the world.

Dimensions (mm)	Dimensions (in.)	Region
1219 x 1016	48 x 40	North America
1200 x 1000	47.24 x 39.37	Europe, Asia
1165 x 1165	45.90 x 45.90	Australia
1067 x 1067	42 x 42	North America, Europe, Asia
1100 x 1100	43.30 x 43.30	Asia
1200 x 800	47.24 x 31.50	Europe

1.5 Structure of Pallet Fasteners

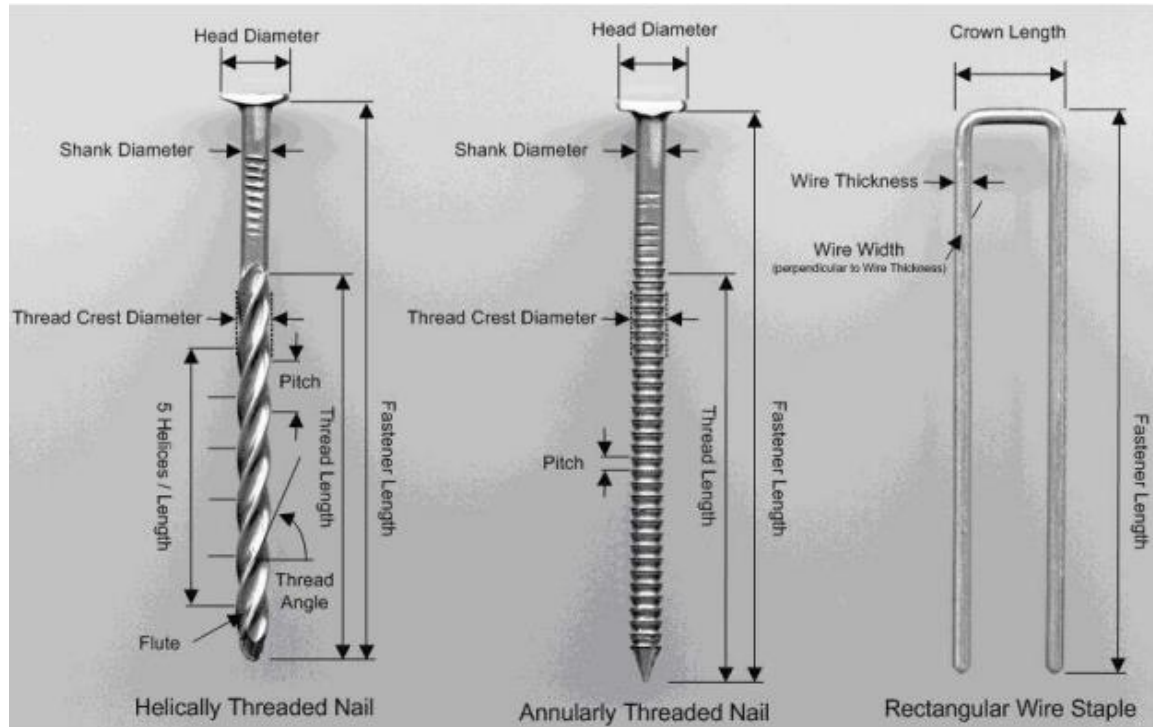


Figure 4: Fastener designs showing components of each fastener type adapted from: (Uniform Standard for Wood Pallets 2014)

1.5.1 Fastener Length

The fastener length for nails and screws is the measured distance of the axis of the shank of the fastener, beginning at the maximum diameter of the head to the tip endpoint of the fastener. As demonstrated in **Figure 4**. The fastener length of a staple is the distance, measured corresponding to the staple-leg axis, from the bottom of the crown to the top endpoint of the fastener. The amount of withdraw resistance a fastener has is directly related to the depth that the fastener is embedded in the wood (Stern, 1956). If a fastener is not imbedded far enough, it will have less withdrawal resistance than if the fastener was longer. If the fastener is too long, then the fastener may not have as much friction, used to connect with the wood fibers, and the withdrawal resistance could also be lower. If the fastener is driven too deeply the strength of the connection will also decrease.

1.5.2 Wire Diameter

The wire diameter of a fastener is defined by the ASTM standard as the length of the longest straight line which can be measured through the center of the cross section of a fastener. For example, when measuring for the wire diameter, the diameter of a plain-shank nail is right below the grip marks of the machining apparatus. The diameter of a threaded shank is measured through the bare shank before the thread is rolled onto the fastener (ASTM, 1995).

1.5.3 Thread Diameter

Threads on pallet fasteners can be categorized into two different groups: helical and annular. These are rolled onto a shank to create the threads; the deformations pass entirely around the body of the fastener (ASTM, 1995). The threads on fasteners allow the fastener to have a greater withdrawal resistance by increasing the friction between the material of the fastener and the wood fibers and grain. The thread diameter is measured across the widest part of the threads which makes it different than the wire diameter which does not take the threads into account.

1.5.4 Thread Helixes

Helical threads are a series of continuous helix depressions which are rolled into the fastener shank which cause a series of resulting expansions nearly equivalent to the depressions (ASTM, 1995). The thread of a helically threaded nail runs approximately two-thirds of the nail length. This is also similar for wood screws. Since the cross-sectional areas before and after the helical threads on a nail are approximately the same, this design's diameter is equal to its wire diameter (Willis, 1996).

1.5.5 Thread Angle

The thread angle of a fastener is the angle at which the ridges are wrapped around the wire relative to the vertical axis. Thread angles need to be precise because there are different types of threads: straight threads and tapered threads. The larger the thread angle, the easier it is to drive in the fastener. Decreasing the angle of the threads leads to an increase in holding power and drive resistance (Stern, 1956).

1.5.6 Fastener Head

The head diameter of a fastener is the distance across the top of the fastener perpendicular to the shank. It is usually created as a deformation of the shank, at or near the end opposite the point. The head is created during the manufacture of the fastener in order to provide area for the fastener to be driven mechanically or manually or offer resistance while the fastening process occurs (ASTM, 2012).

1.6 Type of Fasteners

There are several fasteners intended for wood pallets: wood screws, lag screws, and driven fasteners, such as nails and staples. Nails are by far the most common type of fastener, and structurally, there are three different types of nails. Fluted, threaded, and plain shank nails are the three different types used in pallets. For many years, nails were made with indents, or barbs, that allowed a nail to have more holding power compared to plain-shank nails. However, barbed nails only have more holding power under certain conditions. The indents in barbed nails actually decreased the tight contact between the nail shank and the wood (Stern, 1951). These barbed nails eventually led to the fluted and threaded nails we have today.

1.6.1 Fluted Nails

Fluted nails are typically slenderer than plain-shank nails, so to make up for it, these fluted nails are made using “stiff-stock” wire which contains a higher carbon content than the wire used for plain-shank nails. Fluted nails can provide 50%-200% greater axial holding power compared to plain-shank nails in withdrawal. The heads of fluted nails cannot be uniformly round because of the manufacturing process used to create them. This can cause problems like jamming when attempting to drive in fluted nails (Stern, 1956). A fluted nail is almost identical to a threaded nail; however, fluted nails offer less shear resistance, because they cannot provide the same lateral load carrying capacity as a helically threaded nail with a medium thread angle.

1.6.2 Threaded Nails

Threaded nails or helically fluted nails are another type of fastener. Medium or high carbon steel wire are used for threaded nails (Stern, 1956). There are two main types of threaded nails: helically threaded nails and annularly threaded nails. Thread design is

of prime importance in nail efficiency. If the threads are too shallow, they may not be effective in increasing hold capacity. If they are too deep, then the nail may buckle and decrease its resistance to shear and lateral loading (Stern, 1951). The thread roots of the nail shank are also important when considering how to increase friction between the nail shank and wood fibers which is how nails hold larger loads. For annular nails, a round or wider thread root is considerably more effective than a sharp or thinner thread root. Conversely, for helically threaded nails, a flat thread root is preferred over a round thread root (Stern, 1956).

1.6.3 Plain-Shank Nails

Plain-shank nails are currently one of the three most common nails used in pallet construction. (NWPCA, 2014) They are created using low-carbon steel wire and are the easiest type of nail to manufacture. Fluted and threaded nails were created to try to improve plain-shank nails. Plain-shank nails can also have different withdrawal resistances depending on how the nail is driven into the wood. This phenomenon is more apparent in softwood pallets than hardwood pallets. If a plain-shank nail is driven in parallel to the wood grain, the nail can have 50%-75% more withdrawal resistance compared to a nail being driven perpendicular to the wood grain, based on a study performed by George Stern in 1951 (Stern, 1951). He found that this occurs in softwoods, but in hardwoods, the withdrawal resistance does not change based on orientation.

1.6.4 Screws

A screw is a relatively heavy gauge, pointed, headed fastener designed to be turned by a screwdriver. In their simplest form, screws have a continuous, helical, short-lead thread around a slightly tapered shank from which it projects (Stern, 1951). Parallel twin threads were one of the first basic improvements to screws. This allowed for faster turning into wood without decreasing the screw's holding power. Relieved shank diameter between the head and threads of a screw are another improvement that can allow for tighter fastening of a screw. Length of a screw is a very important factor when considering holding power. If a screw is too wide, the screw could end up splitting the wood into which it was driven, but if a screw is too narrow, the withdrawal resistance could be too low to support the desired load.

1.6.5 Lag Screws

Lag screws are very similar to screws in that they are also helically threaded. They usually have an externally driven square or hex drive head, threads with a large pitch, and are pointed. Lag screws are mostly made of carbon steel, alloy steel, or stainless steel. Lag screws are designed to be installed in prepared pilot holes and then fastened into the wood being guided by the hole. Lag screws are commonly used to attach metal to wood connections, and they are used when it is impractical to use a through-bolt (McLain, 1992). Lag screws can also be used for wood-to-wood connections, for wood-to-wood joints, there are two different pilot holes that must be drilled for each lag screw, via the National design standard for wood construction. Washers are used under the heads of lag screws this helps distribute the load across a larger area rather than just under the lag screw head.

1.6.6 Staples

Staples are a U-shaped wire fastener. They are plain shank, flattened steel, wire fasteners produced by bending wire to form two equally long legs and a flattened crown connecting both of these legs at the ends opposite their points. They are intended to be forced into a material by an automatic strike with electric, pneumatic, or manual tools. These fasteners then hold varying layers of materials together (Spasojevic, M et al. 2021). Staples come in many different sizes, and they are either bright or coated. The withdrawal resistance of staples depends directly on the circumference of the wire and the depth to which the staple has been inserted in the wood (Stern and White, 1997).

1.7 Fastener performance

1.7.1 Withdrawal

The principal mechanical properties that determine fastener performance are driving resistance, withdrawal resistance, and lateral load carrying capacity (Stern, 1951). Withdrawal stiffness can be defined as the force required to withdraw the fastener shank from the wood member (Stern & White, 1997). Many researchers have investigated the withdrawal resistance; however, few have studied the withdrawal stiffness of nailed joints. Withdrawal occurs as soon as the friction force between the fastener and the wood

is exceeded (Ehlbeck, 1979). Fasteners also have varying holding capacities depending on whether they are driven into green or conditioned wood. Holding capacity is determined during withdrawal test which attempts to pull a fastener out of the main wood member. A fasteners' holding capacity is related to the depth of penetration of the fastener in the main member (McLain, 1992).

1.7.2 Shear

Shear joints or connections are classified according to the direction of loading relative to the length of the fastener. Connections involving shear have a load applied perpendicular to the length of the fastener (Breyer et al. 2015). The shear connections can be further classified by the number of shear planes. Joints can have multiple types of shear planes. For example, single shear, double shear, and additional shear planes are possible. According to the NDS (Sec. 12.3.9), connections with more than two shear planes are to be analyzed by evaluating each shear plane as a single-shear connection (American Wood Council, 2018).

1.7.3 Head Embedment

Head embedment stiffness is the force required for a fastener head to indent into a wood member. It is a measure of the elasticity of the interaction between the nail head and the wood surface in pounds per inch (Stern & White, 1997). When an actual pallet joint is tested for this phenomenon, there is a stress that develops under the nail head. This can be demonstrated in Equation 1 where the forces present are shown:

$$\sigma_{hp} = \frac{P}{\pi(HD^2 - WD^2)} \quad \text{(Equation 1)}$$

Equation used to calculate the Head embedment stress under a nail head

Where:

σ_{hp} = stress under the nail head (lbs./in²)

P = force on the nail head (lbs.)

HD = head diameter (in.)

WD = shank diameter of the fastener (in.)

Adapted from (Samarasinghe, 1987)

The force underneath the head of the fastener is a function of the specific gravity of the wood member and the surface area of the head of the fastener. Head embedment resistance is the force required to shear a cylinder of wood equal to the head diameter. (Loferski, 1985)

1.8 Fastener Effect on Pallet Load Capacity

1.8.1 Pallet load capacity

The pallet's resistance to deflection while under load is known as the pallet's stiffness. Stiffness is a key factor in determining the load-carrying capacity of a pallet. One of the largest issues in understanding the performance of pallet joints is the number of variables that can influence the behavior of the joint. Many factors have been identified as influential to both the strength and stiffness of a fastened joint. The ASTM D1185 (2017) standard outlines test procedures to understand these variables which was used to determine things like test speed and sample size. A description of some of the factors that have been researched and found to influence load capacity are outlined below.

1.8.2 Testing Standards

There have been several standards developed to investigate the durability, quality, and reliability of pallets over the last 60 years. Two of the most well-known standards for testing pallets are comprehensive guides provided by ASTM and ISO. The ASTM D1185 (2017) standard mainly focuses on two different types of testing. First are static compression and bending tests during which a pallet is put under a compressive load to determine the maximum safe load that it can hold. These tests can also provide info such as strength, stiffness, and safe working load or safety factors for a specific pallet while in a distribution environment. The second type of tests are the dynamic tests which are used to estimate the functionality and physical durability of a pallet in specific shipping and material handling environments. The ISO 8611 (2021) standard was developed to simulate the normal material handling operations that a pallet will experience within a warehouse environment. This standard is composed of different sections which are used

to determine the load capacity and the maximum working load under various support conditions (similar to the ASTM standard).

1.8.3 Pallet Design Software

The Pallet Design System (PDS) was developed in 1984 for the wood pallet industry. Since its inception, it has become a tool used throughout the material handling industry. PDS is constantly updated with new versions that incorporate improved estimates from data gathered through rigorous testing and research. PDS allows users to fill out the specifications for a pallet's type, size, and construction. The software allows the construction to be completely customizable. All of the components can be moved or swapped with a variety of materials. This includes various wood species, recycled components, and even a variety of plastics. The fasteners used in manufacturing the pallet can also be changed depending on the specifier's needs. PDS provides a 2-D drawing of the customized pallet based on user input. Information about the structural, durability, and physical properties analysis is provided and can be updated as changes are made to the pallet design. The software will run an analysis of the load that is intended to be placed on the pallet, whether it is uniformly distributed or a concentrated load. PDS will then give a detailed report of the pallet's expected performance based on the load on the pallet will be carrying, including the number of trips that the pallet can be expected to survive. Comparisons can be made between the performance of different pallet designs, wood species or grades, fasteners, and component dimensions.

1.8.4 Effect of Loading

The effects of loading known as the load capacity of a pallet can be determined using laboratory testing or computer modeling. Laboratory tests using standards like ISO 8611 (2021) or ASTM D1185 (2017) are an accurate way of assessing a pallets' load carrying capacity. The standards in question require a series of bending tests using multiple repetitions to estimate the load capacity. ASTM D1185 recommends pallets to be loaded with a flexible airbag while ISO 8611 recommends using rigid bars. Both methods are designs to provide a comparative performance evaluate for pallets. The testing standards also allow pallets to be loaded with actual products where the size or type of products,

stacking pattern and used containment force all can have a major effects on the testing results.

Box size has a significant effect on the deflection of pallets in a warehouse environment. This effect was especially significant for warehouse support conditions where pallets were racked across the width or length. As much as a 53% reduction in pallet deflection was observed for high-stiffness pallets supporting corrugated boxes with 25.4 mm headspace, when the size was increased from small to large boxes. (Clayton et al. 2019). Clayton et al. (2019) concluded that the increased concentration of compression stresses from boxes on top of the supports and the resulting lower pallet deflection could significantly increase the actual load carrying capacity of some pallet designs.

There are four main patterns into which products can be stacked on a pallet. These include column stacking, interlocked stacking, pinwheel pattern, or creating a custom stacking pattern. In 2017, pallet stacking was investigated, when the layers of boxes on a pallet are interlocked, the pallet is subject to lower deflection (up to 53%) (Molina, 2017). Once the product is put on the pallet, stretch wrap or banding can be applied to the pallet to keep the product from slipping or moving. Depending on how this is applied, it will also cause different stresses on the pallet components and joints. The type of containment method, in addition to the force that is applied while securing the load, significantly affects rigidity of the load, affecting unit load and pallet deflection. The experimental results of a 2018 study indicate that an increase in the containment force provided by stretch wrap can improve the unit-load deflection by as much as 81% (Park et al. 2018).

1.8.5 Effect of Supports

When pallets are used in warehouses, they are stored using a variety of different racking conditions. Differing racking conditions directly affect pallet load capacity and rate of deflection. Pallet deflection has a direct effect on the durability and longevity of a pallet throughout the material handling system. Excessive pallet bending can result in pallet failure which can lead to mechanical handling system malfunction, personal injury, or product damage. Therefore, the ANSI MH1 standard provides guidelines on

acceptable amounts of bending and the maximum allowed deflection of a pallet that is intended for use in warehouses.

1.8.6 Joint Rigidity

The joints between the deckboards and stringers also have a major effect on the performance of the pallet. The stiffness of these joints is largely dependent on the fastener used to connect the main member of that joint to the side member, as well as the species of wood from which the joint is constructed (Breyer et al., 2015). Joint stiffness influences the deflection characteristics and load carrying capacity of the pallet. When the pallet is racked across the deckboards in racked storage, the greatest impact of joint stiffness is on the pallet's deflection. Due to load instability, this deflection may, at worst, result in a life-threatening situation; however, it is more likely to result in significant issues with serviceability. Several studies (Stern 1971, 1974, 1978; Stern and Wallin, 1976) have determined the strength and stiffness of wood pallets. Stern dealt with overall pallet performance as affected by species of wood and type of fastener.

2 INTRODUCTION

Distribution is one of the largest industries in the world and has a storied past. Humans have always had the need to transport goods from one place to another. The main way that this need has been fulfilled is by using platforms on which people could stack their goods. Pallets are the main way on which goods are shipped today, and the modern pallet rose to popularity because of an invention which made distribution on pallets very practical: the forklift. Forklifts started being used in 1887 and were improved during the 1900s (LeBlanc, 2002). A majority of pallets used in the industry today are wooden with 95% of the companies' using pallets made of wood (McCrea 2022). Many of these are single-use pallets that are created with new lumber. In 2016, 508 million new wood pallets were produced in the U.S. by various companies in the pallet market. This was an increase of 22% compared to 2011 when it was estimated 416 million new pallets were produced that year (Gerber et al., 2020). The load that a pallet can hold is determined by the materials and the construction of the pallet. The construction of a pallet can refer to entry type, style, top deck construction, bottom deck construction, pallet component dimensions, type of fastener, or species of wood used. The mechanical properties of the lumber used in pallet construction has also been investigated in great depth, in both the building construction industry and the wood science industry (Peters, 1985) (Winistorfer and Soltis, 1994) (White and Clarke, 1998). The NDS (National Design Specification for Wood) created by the American Wood Council goes into great depth discussing the strength values for differing types of lumber and fasteners. While strength values are well documented, the stiffness values that result from the joints in wooden pallets have not been studied as much. There was only one study that addressed this issue by Sandhya Samarasinghe (1987) that predicted the rotational stiffness of pallet joint using nails. In the study, the rigidity of the pallet joint was represented with three stiffness values including representing the three factors that greatly impact the stiffness of a pallet joint. Samarasinghe also developed a model to predict the rotational stiffness using three the three measured spring constants. The model developed in this study is currently being used to predict the rotational stiffness pallet joints secured with common pallet nails. Although, the developed more can be effectively used for predicting the joint

rigidity of nail pallet joints but the applicability of the model for alternative fasteners such as lag screws and carriage bolts was never investigated. In addition, the critical three stiffness values were never measured for alternative fasteners.

3 OBJECTIVE

The main objective of this project was to investigate the performance of pallet joints made from carriage bolts and lag screws and using different species of wood.

The specific objectives of the study are listed below:

- To quantify the head embedment, shank withdrawal, and edge crushing stiffness of pallet joints made using lag screws and carriage bolt.
- To investigate the effect of fastener size and type on head embedment, shank withdrawal, and edge crushing stiffness of pallet joints.
- To investigate the effect of wood species on head embedment, shank withdrawal, and edge crushing stiffness of pallet joints.
- To investigate the correlation between wood specific gravity and head embedment, shank withdrawal, and edge crushing stiffness of pallet joints.

4 MATERIALS

Two different species of wood, including southern yellow pine and red oak, were used for the study. The wood boards and blocks were provided by Hopkins Lumber (Ridgeway, VA). Half of the pine samples were tested in a green condition, while the other half were tested at a 19% moisture level. The oak samples were only tested in green condition. To achieve the kiln-dried moisture content of 19%, an environmental chamber (Thermo Fisher Scientific 3920 Forma Environmental Chamber, model: 3940) was used. The wood samples were conditioned at 88% relative humidity and 75 degrees Celsius until 19% moisture content was reached. The green samples were kept under water to ensure their moisture level stayed above the fiber saturation level (> 30%). To measure the moisture content of the wood boards and blocks, a small sample was cut from every board and block. These samples were tested for moisture content using the oven dry method from the ASTM D 4442 (2020) standard.

The sizes of these deckboards were 3.125 in. by 0.75 in. by 20 in. This size was chosen to simulate a pallet top deck board, and while many heavy-weight pallets are

made with thicker deckboards, we are using this size to stay consistent with the original study done by Samarasinghe (1987). This was also done to replicate the model developed in that study and make it as comparable as possible.

The sizes of the blocks used for this study were 3.125 in. x 3.125 in. x 3.125 in. They were cut and planed down to this size. This size was chosen to simulate a standard size of pallet blocks used in the pallet industry. This was also the size used in the original study conducted by Samarasinghe (1987).

Six different types of alternative fasteners were investigated during this study, including: 0.25 in. lag screws, 0.375 in. lag screws, 0.5 in. lag screws, 0.25 in. carriage bolts, 0.375 in. carriage bolts, and 0.5 in. carriage bolts. The complete list of alternative fasteners and materials is presented in **Table 2**. All of the materials were purchased from The Home Depot.

Table 2: A complete list of alternative fastener materials used for testing.

Description	Quantity	Units	Model #
3/8 in.-16 x 3-1/2 in. Galvanized Carriage Bolt (25-pack)	100	4	#803540
1/2 in.-13 x 3-1/2 in. Galvanized Carriage Bolt (25-pack)	100	4	#804696
1/4 in.-20 x 3-1/2 in. Galvanized Carriage Bolt (10 pack)	90	9	#805066
3/8 in. x 3-1/2 in. Hex Galvanized Lag Screw (25-pack)	100	4	#810320
1/2 in.-13 x 3-1/2 in. Hex Galvanized Lag Screw (25-pack)	100	4	#804680
1/4 in.-20 x 3-1/2 in. Hex Galvanized Lag Screw (25 pack)	100	4	#803740
1/4 in.-20 Galvanized Hex Nut (100-pack)	100	1	#804040
1/2 in.-13 Galvanized Hex Nut (50-pack)	100	2	#804070
3/8 in.-16 Galvanized Hex Nut (100-Pack)	100	1	#804060
3/8 in. Galvanized Flat Washer (100-Pack)	100	1	#807290
1/2 in. Galvanized Flat Washer (50-Pack)	100	2	#807300
1/4 in. Galvanized Flat Washer (100-Pack)	100	1	#807270

The conditioned blocks for the shank withdrawal and moment rotation tests had holes drilled into them using a drill press. (Atlas Press Company; model number: 1020). To create pre-drilled or lead holes, the NDS (National Design Specification) (2018) for wood construction was followed for both the lag screws and carriage bolts sample construction.

The clearance holes for the carriage bolts were 1/16th in. larger than the bolt diameter for all three carriage bolt sizes. The carriage bolts were all counter sunk into the

blocks during testing. A standard 1 in. depth was used during all the countersinking. The counter sink hole was 1/16th in. larger than the size of the washer used with the bolts during testing.

The clearance holes for the lag screws' shanks had the same diameter as their shanks, and the same depth of penetration as the length of the unthreaded shank. The lead hole for the threaded portion of the lag screws had a diameter equal to 75% of the shank diameter, and the depth was equal to that of the length of the threaded portion of the shank.

5 METHODS:

5.1 Modulus of Elasticity

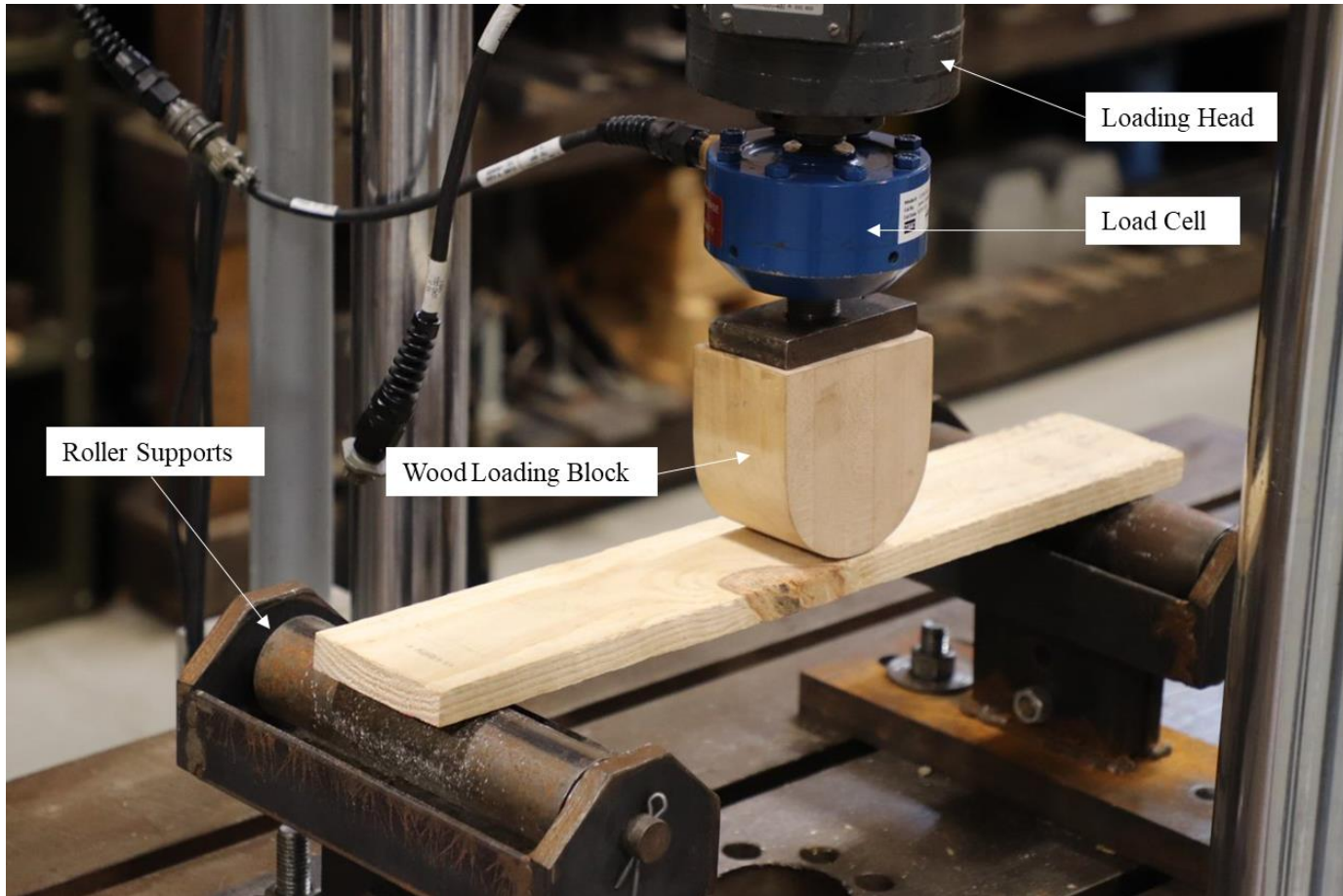


Figure 5: Picture of experimental setup used for the measurement of the Modulus of Elasticity values.

The 3.125 in. x 0.75 in. x 20 in. deckboards were tested to determine the Modulus of Elasticity (MOE) of the boards. This was done using a three point bending test based on the ASTM D 143 (2020) testing standard using a universal testing machine (MTS, Eden Prairie, Minnesota, United States) equipped with 5,000 lbs. load cells (Model 1210AE-5K-B, ser. No. 77962A, MTS, Eden Prairie, Minnesota, United States). The samples were set up on two roller supports (1 in. diameter) that were spaced 18 in. center to center. The roller support assembly was 4.25 in. tall (**Figure 5**). The load was applied via a wooden loading block with a 1.5 in. radius at a single point in the middle of the

sample. The load rate was 0.05 in. per minute and the load was increased until the deflection of the deckboard reached 0.02 in. which is below the elastic limit according to the wood science handbook (Forest Products Laboratory, 2021). After the data was recorded, the wood specimens were cut in half and used in both the head embedment test and the moment rotation testing.

To calculate the MOE, two points on the load-deflection curve were selected and the change in load and the change in board deflection were calculated between the two points. The width and thickness of the board was measured at mid span using a caliper (Mitutoyo Model number CD-12" AX) with a 0-12 in. range and 0.0005 in. sensitivity. Equation 2 was used to calculate the Modulus of Elasticity value.

$$E = \frac{\Delta Pl}{4\Delta dwt^3} \quad (\text{Equation 2})$$

E = Modulus of Elasticity

ΔP = Change in load

l = Length of the board between the supports

Δd = Change in deflection of the board

w = width of the board

t = thickness of the board

After the MOE was calculated, the average MOE for each wood species was determined at each moisture content level, and the COV was calculated.

A model was developed by Samarasinghe (1987) to predict the measured rotational stiffness of pallets according to the nails which were used. The model consists of three stiffness values that must be calculated, including: head embedment stiffness, shank withdrawal stiffness, and moment rotation stiffness.

5.2 Head Embedment Test

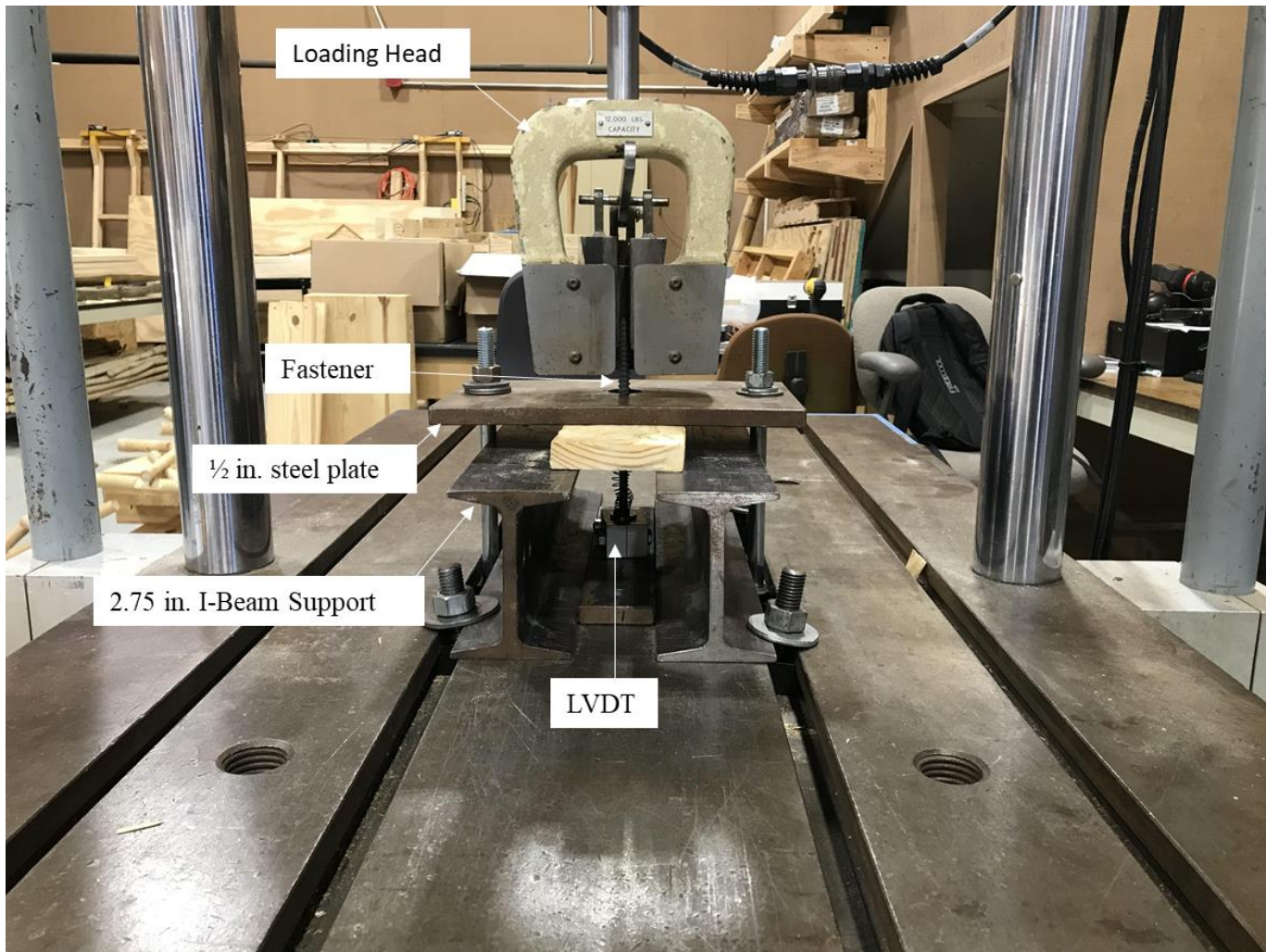


Figure 6: Picture of experimental setup used for the determination of the Head Embedment Stiffness.

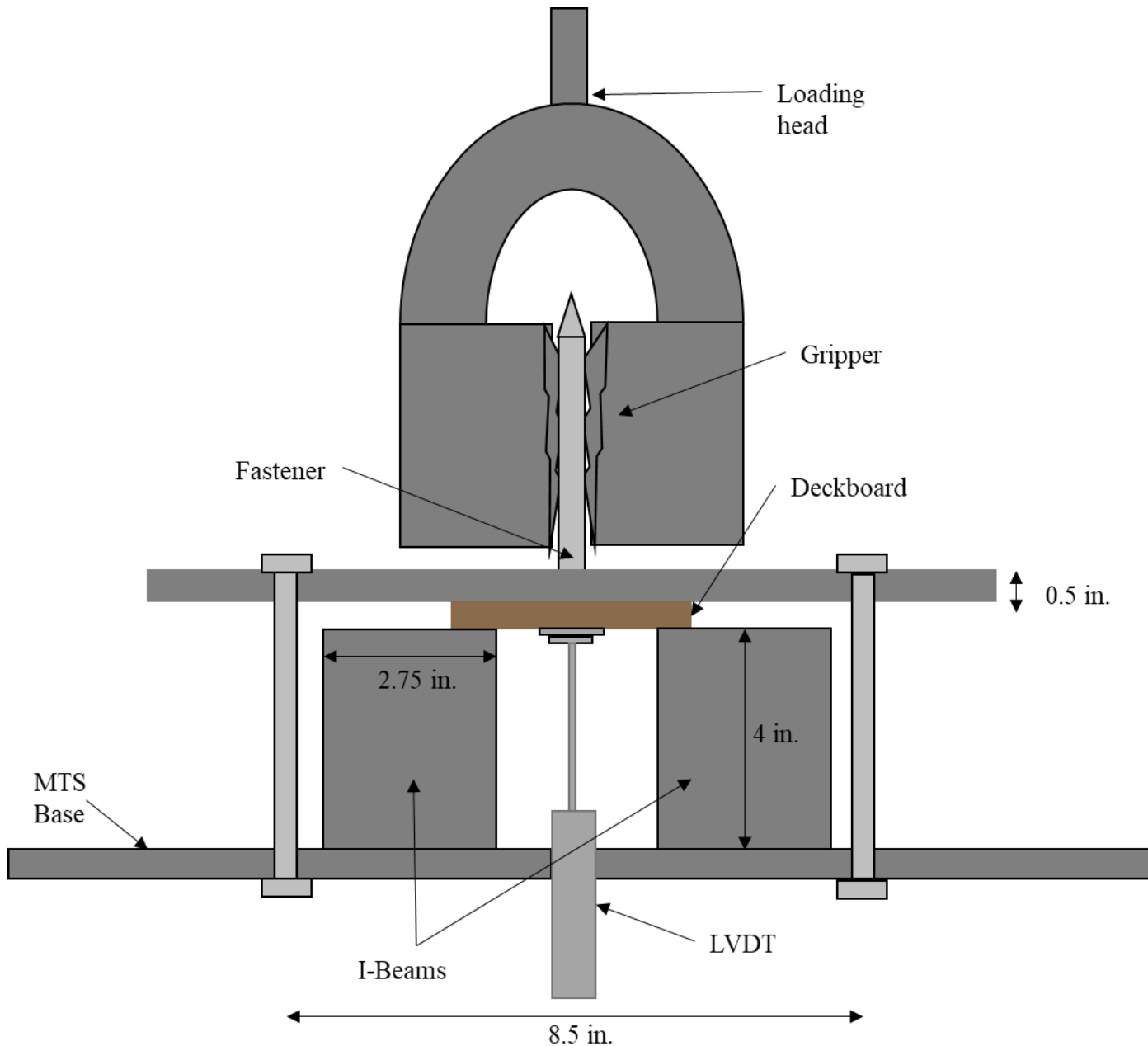


Figure 7: Model showing the components of the Head Embedment Test.

The head embedment test presented in Figures 6 and 7 was used to predict the head embedment stiffness. The test was conducted following the guidelines of the ASTM D 1761 (2020) standard and was based on previous work done by Samarasinghe (1987). A universal testing machine (MTS, Eden Prairie, Minnesota, United States) equipped with 20,000 lbs. load cell (model 661.21A-03, ser. No. 4016, MTS, Eden Prairie, Minnesota, United States) was used for all testing. Specimens were assembled by

inserting the investigated alternative fastener into a pre-drilled hole in the wooden board. For the lag screw, a washer was placed between the head of the fastener and the wooden board. Washers were not used for carriage bolts. The wooden board with the alternative fastener was placed upside down on two I-beams which were 2.75 in. wide and 4 in. tall. The board was clamped using a ½ in. steel plate to prevent bending in the specimen. The steel plate was attached to the MTS base using threaded rods. A Linear Variable Differential Transducer (LVDT) (2 in. range, 0.0001 in. sensitivity) was placed under the head of the alternative fastener to measure the amount head embedment (**Figure 7**). The threaded shank of the alternative fastener was firmly held by a gripping mechanism to prevent slippage. A crosshead speed of 0.1 in./min. was used to pull the shank of the alternative fastener and cause the head to embed into the wooden board.

5.3 Shank Withdrawal Test

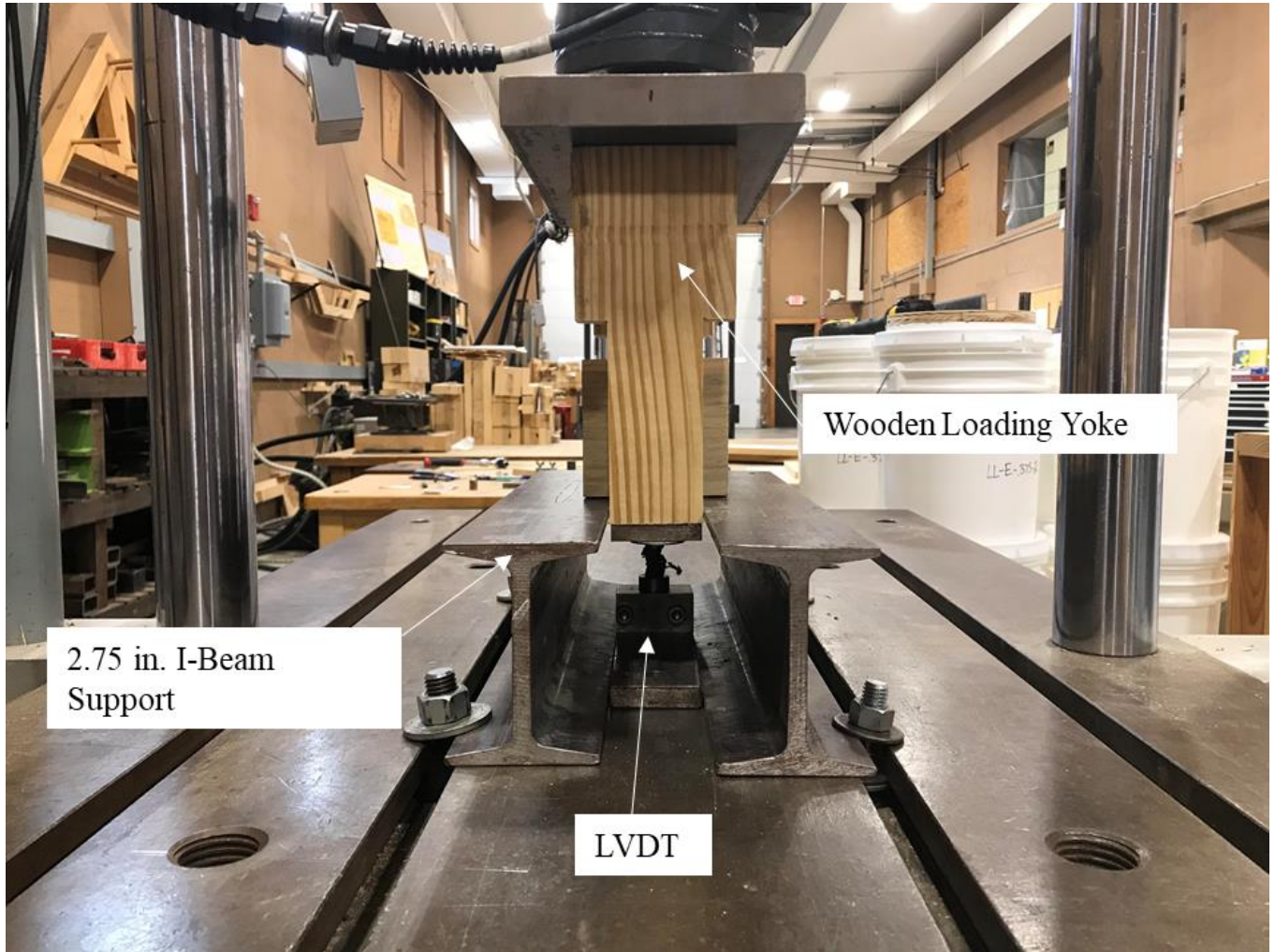


Figure 8: Picture of experimental setup used for the determination of the Shank Withdrawal Stiffness.

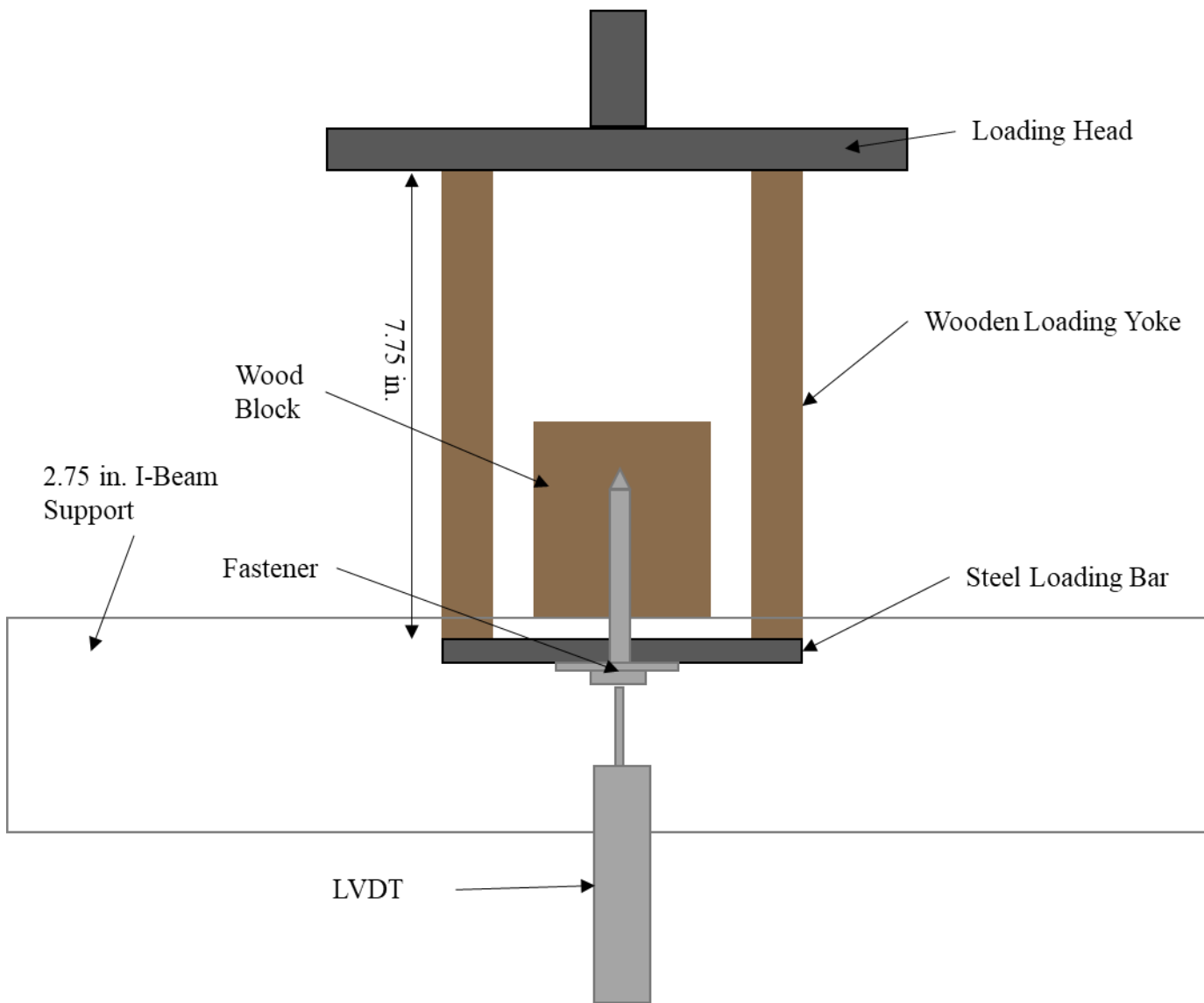


Figure 9: Model showing the components of the Shank Withdrawal Test.

The shank withdrawal test presented in Figures 8 and 9 was used to predict the shank withdrawal stiffness. The test was conducted following the guidelines of the ASTM standard D 1761(2020) and based off previous work done by Samarasinghe (1987). A universal testing machine (MTS, Eden Prairie, Minnesota, United States) equipped with 20,000 lbs. load cell (model 661.21A-03, ser. No. 4016, MTS, Eden Prairie, Minnesota, United States) was used for all testing. The setup involved screwing alternative fasteners into 3.125 in. by 3.125 in. by 3.125 in. properly conditioned wooden

blocks. The alternative fasteners were inserted through a steel loading bar and screwed into the side grain of the blocks which were prepared with pre-drilled holes following NDS specifications. The block was supported on each side with rigid supports, and a LVDT (2 in. range, 0.0001 in. sensitivity) was placed in the middle of the block against the head of the alternative fastener to accurately measure nail movement relative to the block as seen in **Figure 9**. The steel bar which is in between the block and the alternative fastener was pushed on by a wooden yoke which was attached to the MTS cross section head, and a load was applied at 0.1 in./min following the standard mentioned earlier (ASTM D 1761). The block rested on two I-beams which had a bearing area of 2.75 in. and a height of 4 in. This was the second stiffness needed to be plugged into the predictive model.

5.4 Moment Rotation Test

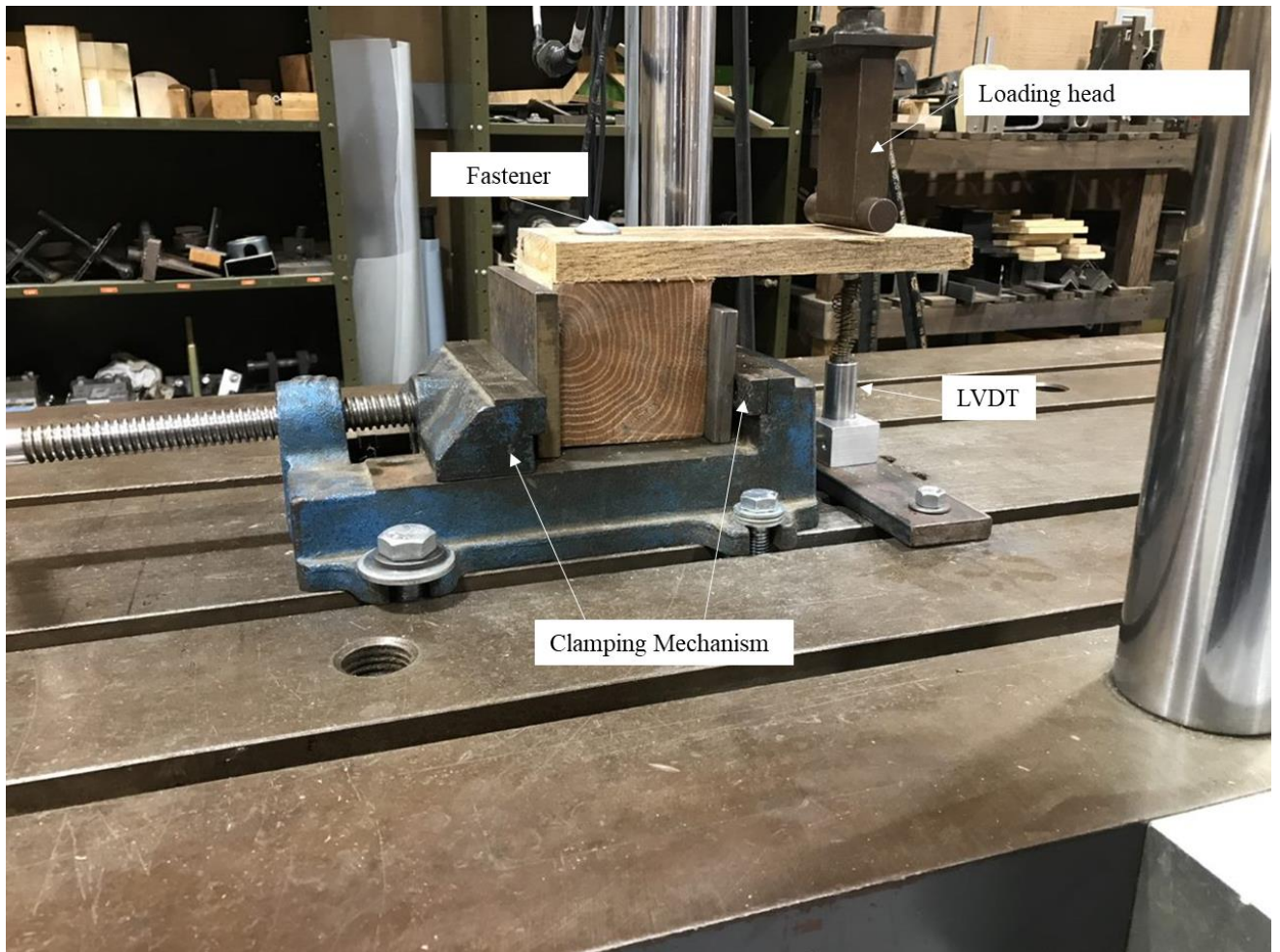


Figure 10: Picture of experimental setup used for the determination of the Edge Crushing Stiffness values.

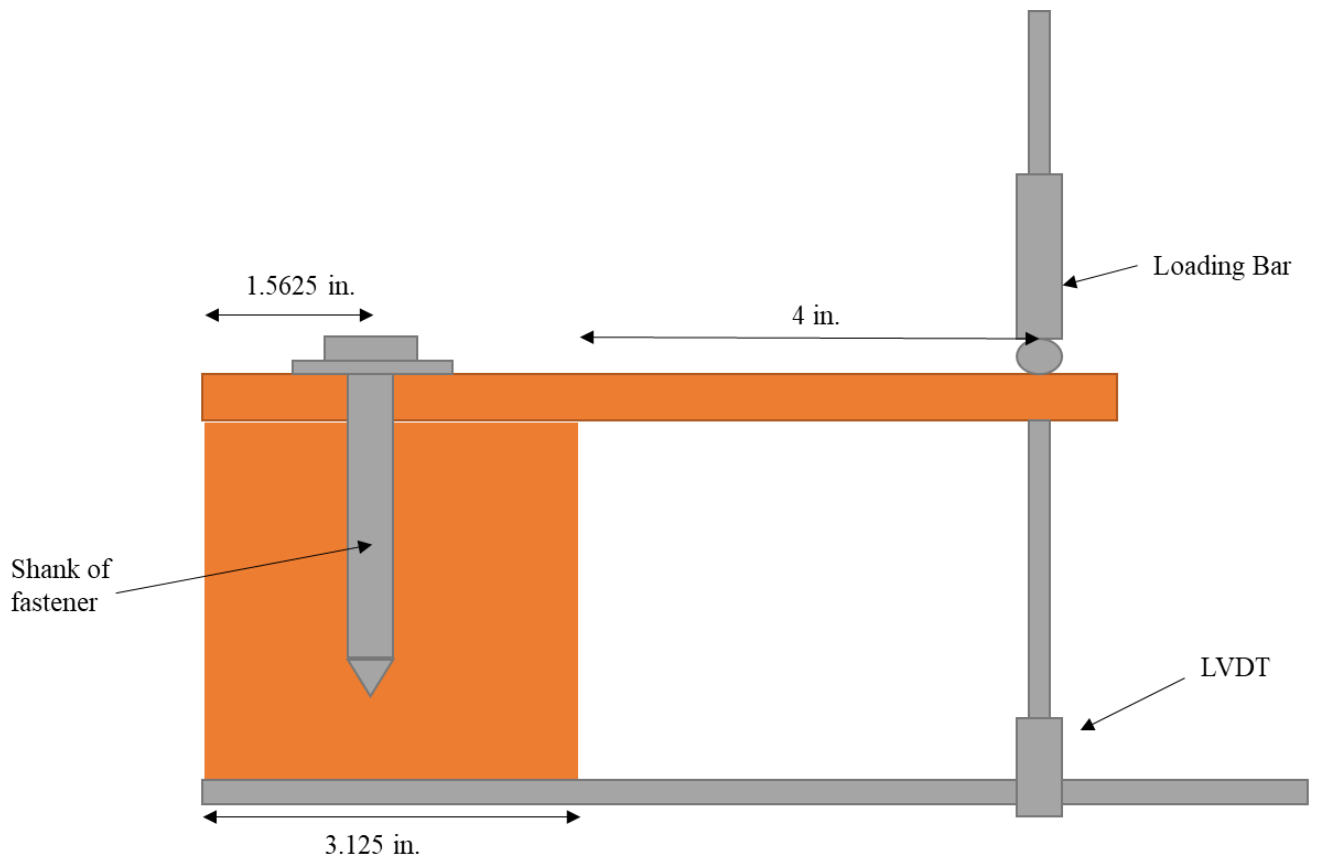


Figure 11: Model showing the measurements used in the Moment Rotation Testing.

The moment rotation test presented in Figures 10 and 11 was used to predict the edge crushing stiffness of the pallet joint. To ensure that all the deckboards used for the moment rotation testing have a characterized MOE value, the deckboards used for the testing were cut from the deckboard samples used during the MOE testing. A universal testing machine (MTS, Eden Prairie, Minnesota, United States) equipped with 5,000 lbs. load cell (Model 1210AE-5K-B, ser. No. 77962A, MTS, Eden Prairie, Minnesota, United States) was used for all testing. The alternative fasteners were screwed through the deckboard into the side grain of the blocks. The holes used in the blocks were predrilled according to the NDS (National Design Specification) (2018) for wood construction was followed for both the lag screws and carriage bolts sample construction. The outline of this process can be seen at the end of the materials section.

The samples were then rigidly clamped to the base of the MTS machine, and a LVDT (2 in. range, 0.0001 in. sensitivity) was placed 4 in. from the inner edge of the

block. The LVDT measured the deflection of the deckboard joint during testing. A load was applied above the deckboard in line with the LVDT at a rate of 0.256 in./min. using a loading head attached to a 5,000 lbs. load cell. This was done to replicate the original testing done by Samarasinghe (1987). This setup was repeated with every wood and alternative fastener combination.

The Moment Rotation testing was performed with a loading speed of 0.256 in./min. while the Modulus of Elasticity testing was performed with a loading speed of 0.05 in./min. the difference in this loading speed was a variable that was not accounted for in the initial test setup of this project. This loading speed is a limitation of this study and future projects may want to consider taking this variable into account.

After all the samples were tested, the moisture content was determined following the ASTM D-2395 Standard – Method A. The length, width and thickness of the specimens were measured. The initial mass is taken before oven-drying. After the specimen was oven-dried the mass was taken again and the moisture content was determined. The specific gravity was calculated by measuring the sample again after it was oven dry. The oven dry mass was divided by the oven dry volume and that provided the oven dry density of the samples. The oven dry density was converted to lbs./ft³ and this density was divided by the density of water, 62.4 lbs./ft³. This method was chosen because of the methods adaptability to accommodate any size sample. A Mitutoyo caliper (Model CD-12" AX) was used to collect sample measurements. Three measurements of each dimension were taken, and the average was used.

6 Calculations:

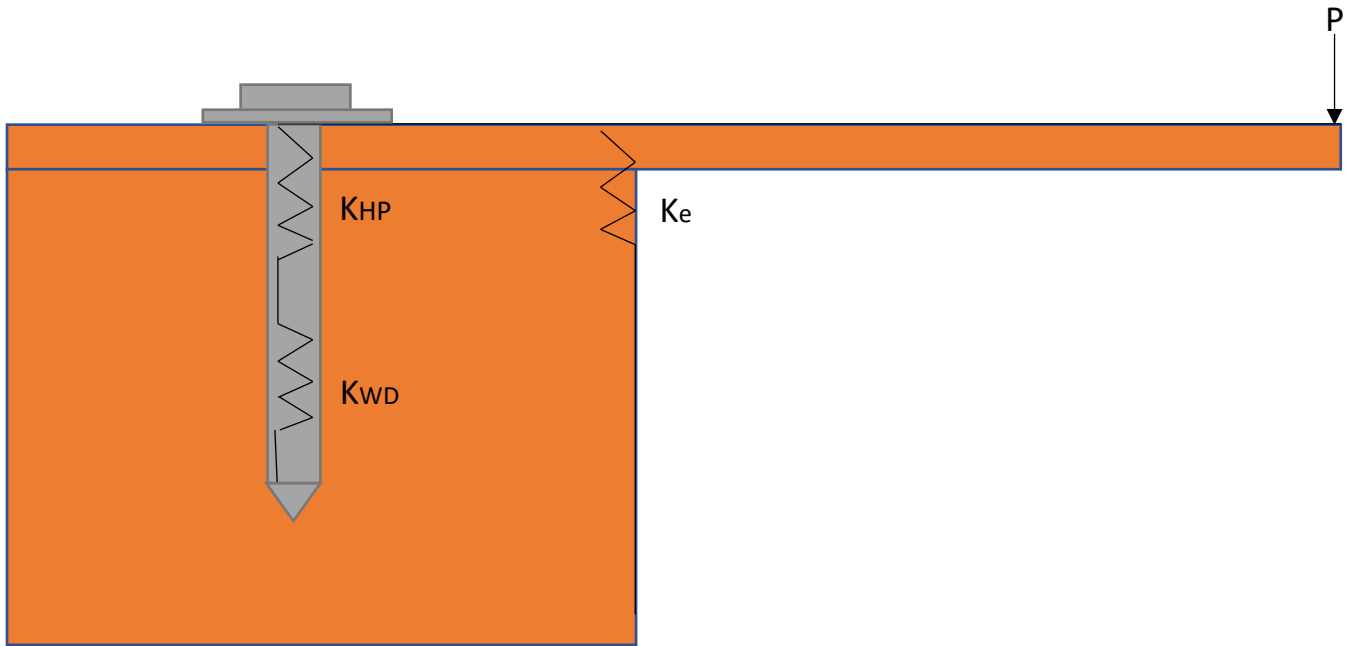


Figure 12: Schematic model showing the locations of the three springs that can be used to describe the rigidity of pallet joints.

In the investigate pallet joints the three stiffnesses investigated can be seen in **Figure 12**. The pallet block in figure 12 shows three “K” values which are the three stiffnesses that affect the stiffness of a pallet joint. The K_{HP} is the stiffness of the head embedment of the alternative fastener into the deckboard. The K_{WD} is the stiffness of the fastener as the shank of the alternative fastener is withdrawn from the block. Lastly, the K_e is the stiffness of the block as the edge of the block is crushed by the deckboard. These three “K” values were the three that were tested for and the calculations for the values for each pallet joint are outlined below.

6.1 Calculations for Head Embedment and Shank Withdrawal Stiffnesses

The head embedment and shank withdrawal stiffnesses were calculated from the load-deformation curve obtained from the head embedment and shank withdrawal tests for each specimen. The stiffness values were calculated from two points selected on the

linear portion of the load-deformation curve. The equations are listed in Equation 3 and 4. The calculated stiffness values for each replicate were averaged together.

$$K_{HP} = \frac{\Delta P_1}{\Delta d_1} \quad (\text{Equation 3})$$

K_{HP} = Stiffness (lbs./in.)

ΔP_1 = change in load during the head embedment test (lbs.)

Δd_1 = Change in the head embedment of the alternative fastener into the board (in.)

$$K_{WD} = \frac{\Delta P_2}{\Delta d_2} \quad (\text{Equation 4})$$

K_{WD} = Stiffness (lbs./in.)

ΔP_2 = change in load during the shank withdrawal test (lbs.)

Δd_2 = Change in the shank withdrawal of the alternative fastener from the block (in.)

After the stiffnesses were calculated at multiple points, the average stiffness was taken for each alternative fastener and wood combination and the COV was calculated.

6.2 Edge Crushing Stiffness (K_e) Calculation

Edge crushing stiffness (K_e) value was calculated from the results of the moment rotation, head embedment and shank withdrawal tests. The schematics of the moment rotation test are presented in **Figure 9**. During the moment rotation test, the total deflection of the pallet deckboard (D_{Act}) is influenced by four factors which include, crushing of the edge of the block or stringer due to the bending of the deckboard (D_e), the rigid body motion of the deckboard (D_{Rot}), the bending of the deckboards due to the applied load which is composed of a component due to the Modulus of Elasticity (D_b), and the shear Modulus (D_s) of the board (Equation 5).

$$D_{Act} = D_{Rot} + D_s + D_b + D_e \quad (\text{Equation 5})$$

D_{Act} = Total deflection observed (in.)

D_{Rot} = Deflection due to pure rotation (in.)

D_s = Deflection due to shear (in.)

D_b = Deflection due to deckboard bending (in.)

D_e = Deflection due to edge crushing (in.)

The total deflection of the board (D_{Act}) is measured during the moment rotation test. The deflection from rigid body rotation (D_{Rot}), and the deflections from board bending and shear, (D_b , and D_s), can be calculated from the result of the three-point bending, head embedment and shank withdrawal tests using equations 7, 8 and 9. Thus, the deflection from edge crushing can be calculated using equation 6, since all the other variables in equation 6 are known.

$$D_e = D_{Act} - (D_{Rot} + D_b + D_s) \quad (\text{Equation 6})$$

D_e = Deflection due to edge crushing (in.)

D_{Act} = Total deflection observed (in.)

D_{Rot} = Deflection due to pure rotation (in.)

D_b = Deflection due to deckboard bending (in.)

D_s = Deflection due to shear (in.)

The first of the four variables needed to calculate deflection due to edge crushing is the deflection due to ridged body rotation which can be calculated using equation 7 below.

$$D_{Rot} = \frac{P * L^2}{K_{WH} * (\frac{B}{2})^2} \quad \text{(Equation 7)}$$

D_{Rot} = Deflection due to pure rotation (in.)

P = applied load during the moment rotation test (lbs.)

L = Length of the board beyond the edge of the block (in.)

K_{WH} = Combined stiffness the withdrawal and head embedment stiffness (lbs./in.)

B = width of the block (in.)

The second of the four equations used to calculate deflection due to edge crushing is the deflection due to shear which can be calculated using the equation 8 below. Based on the NDS, National Design Specifications for Wood, the Shear Modulus of the board was approximated to 1/16th of the MOE.

$$D_s = PL \frac{12L}{5 \frac{E}{16} b d B} + \frac{6}{5 \frac{E}{16} b d} \quad \text{(Equation 8)}$$

D_s = Deflection due to shear (in.)

P = load (lbs.)

L = Lever arm (in.)

E = Modulus of Elasticity (psi)

B = width of the block (in.)

b = width of the deckboard (in.)

d = depth of the deckboard (in.)

The third of the four equations used to calculate deflection due to edge crushing is the deflection due to bending, because wood is a non-rigid material, the bending of wood will be completely dependent on the MOE for each type of wood. This can be calculated using equation 9 below.

$$D_b = \frac{BL}{6EI} + \frac{L^2}{3EI} \quad (\text{Equation 9})$$

D_b = deflection due to bending (in.)

B = Width of block (in.)

L = Lever arm (in.)

E = Modulus of Elasticity of the deckboard (psi)

I = (width*thickness³)/12 (in⁴)

Finally, the fourth and final component is the deflection due to edge crushing which as mentioned earlier can be calculated by subtracting all the other deflections from the total actual deflection. This can be seen in equation 10.

$$D_e = D_{Act} - \left(\frac{(P*L^2)}{K_{WH}*\left(\frac{B}{2}\right)^2} + \left(\frac{BL}{6EI} + \frac{L^2}{3EI} \right) + PL \frac{12L}{5\frac{E}{16}bdB} + \frac{6}{5\frac{E}{16}bd} \right) \quad (\text{Equation 10})$$

D_e = Deflection due to edge crushing (in.)

D_{Act} = Total deflection observed (in.)

P = load (lbs.)

L = Lever arm (in.)

E = Modulus of Elasticity (psi.)

K_{WH} = Combined stiffness the withdrawal and head embedment stiffness (lbs./in.)

B = width of the block (in.)

b = width of the deckboard (in.)

d = depth of the deckboard (in.)

$$I = (\text{width} * \text{thickness}^3) / 12 \text{ (in}^4\text{)}$$

After estimating the board deflection due to edge crushing, equation 11 can be used to calculate the edge crushing stiffness (K_e).

$$K_e = \frac{P(L+l)}{(l * D_e)} \quad \text{(Equation 11)}$$

K_e = Stiffness due to edge crushing (lbs./in.)

P = load (lbs.)

L = Lever arm (in.)

l = half width of the block (in.)

D_e = Deflection of the board due to edge crushing (in.)

7 Statistical Analysis:

An analysis of variance (ANOVA) test was used for the statistical analysis. Stiffness was the dependent variable, whereas the independent variables were species of wood, fastener size, and fastener type. The analysis was run individually for each test type performed. The model is presented in Equation 12.

$$y_{ij} = \mu + W_s + F_s + F_t + W_s F_s + W_s F_t + F_s F_t + F_s F_t W_s + e_{ij} \quad \text{(Equation 12)}$$

Where y_{ij} = stiffness, μ = overall mean, W_s = species of wood used, F_s = fastener size, F_t = Fastener Type, $W_s F_s$ = interaction effect between wood species and fastener type, $W_s F_t$ = interaction effect between wood species and fastener size, $F_s F_t$ = interaction effect between fastener type and fastener size, $F_s F_t W_s$ = interaction effect between fastener type and fastener size and wood species, and e_{ij} = random error. A Tukey's honestly significant

difference (HSD) multiple comparison analysis was conducted to understand the levels of difference between wood species, fastener size and fastener type with an alpha of 0.05.

8 Results and Discussion

8.1 Shank Withdrawal Stiffness:

The calculated shank withdrawal stiffness values for the investigated alternative fasteners using the three wood species are presented in **Table 3**.

Table 3: Calculated Shank Withdrawal Stiffness for Each of the Three Wood Types.

Fastener Types		Shank Withdrawal Stiffness (lbs./in.)		
		KD-19 Pine	Green Pine	Green Oak
Carriage Bolt	1/4 in.	32,060 (17.5)	28,855 (19.8)	37,234 (17.2)
	3/8 in.	35,901 (16.3)	33,050 (18.1)	44,234 (16.9)
	1/2 in.	42,012 (15.3)	38,592 (22.0)	68,234 (18.5)
Lag Screws	1/4 in.	33,270 (20.7)	32,641 (17.9)	40,564 (20.2)
	3/8 in.	37,987 (16.0)	37,902 (16.6)	48,564 (16.9)
	1/2 in.	41,979 (19.2)	41,352 (20.2)	60,564 (20.7)

Note: Values in parentheses are Coefficient of Variance values in percentages.

The Coefficient of Variance ranged from 15.3-22% for the withdrawal stiffness. This was slightly lower than the COV values seen in the study published by Samarasinghe (1987) using nails which had COV values from 21.5-25.2%. The stiffness values increased as the fastener size increased. The values seen for green oak were also larger than the stiffness values seen for green, and KD-19 pine. The stiffness values seen in the previous study using nails also showed larger stiffness values for the green oak samples compared to the green pine. The values seen for green pine and KD-19 pine were very similar; however, for each fastener type, KD-19 pine had slightly higher values. The COV present in the KD-19 pine was also lower than those seen in the green oak and

green pine samples. The average shank withdrawal stiffness value for the nails used in green oak blocks during the study done by Samarasinghe (1987), was 35,654 lbs./in. The average shank withdrawal stiffness value in green oak blocks for ¼ in. carriage bolts and ¼ in. lag screws was 4.4% (37,234 lbs./in.) and 13.8% (40,564 lbs./in.), respectively, which is greater than what was observed for nails. The average shank withdrawal stiffness value for the nails used in green pine blocks during the study done by Samarasinghe (1987), was 26,803 lbs./in. The average shank withdrawal stiffness of the ¼ in. carriage bolts used in green pine blocks was 8% greater (28,855 lbs./in.) while for the ¼ in. lag screws it was 22% greater (32,641 lbs./in.) compared to nails. To statistically evaluate the effect of wood species, fastener size, and fastener type on shank withdrawal stiffness, an ANOVA test was conducted. The predicted R² value for the ANOVA analysis was 0.71. The effects of wood species ($p < 0.0001$), fastener size ($p < 0.0001$), and fastener type ($p < 0.0492$) on the shank withdrawal stiffness was significant. However, the interactions between these three variables were not significant, so further analysis was not run on these interactions.

To further investigate the effect of the significant variables, a Tukey’s HSD test was conducted. The results of the Tukey test for the wood species, fastener size, and fastener type are presented in **Tables 4-6**.

Table 4: Tukey’s HSD Test for Shank Withdrawal on the Three Wood Types.

Level	Tukey Letter	Least Square Means
Green Oak	A	56052.735
KD-19 Pine	B	36835.791
Green Pine	B	35398.657

Note: Different capital letters represent statistically significant differences between the investigated levels.

Table 5: Tukey’s HSD Test for Shank Withdrawal on Each of the Three Fastener sizes.

Level	Tukey Letter	Least Square Means
1/2	A	49441.609
3/8	B	41883.319
1/4	C	36962.255

Note: Different capital letters represent statistically significant differences between the investigated levels.

Table 6: Tukey’s HSD Test for Shank Withdrawal on Each of the Fastener Types.

Level	Tukey Letter	Least Square Means
Lag Screw	A	43850.624
Carriage Bolt	B	41674.165

Note: Different capital letters represent statistically significant differences between the investigated levels.

The Tukey results presented in **Table 4** show that the shank withdrawal value measured using KD-19 pine and green pine were not statistically different from each other, while the shank withdrawal stiffness for green oak samples was greater than both types of pine. Each of the three investigated sizes of fastener resulted in significantly different shank withdrawal values. As the size of fastener increased, the stiffness associated with the fastener increased significantly. The 0.5 in. fasteners had a 34% larger stiffness value than the 0.25 in. fasteners, and had a 18% larger stiffness compared to the 0.375 in. fasteners. When the shank withdrawal values were measured using lag screws compared to carriage bolts, the results showed that the use of lag screws resulted in statistically higher shank withdrawal values. Although the difference was only 5%.

8.2 Head Embedment Stiffness:

The calculated head embedment stiffness values for the investigated alternative fasteners using the three wood species are presented in **Table 7**.

Table 7: Head Embedment Stiffness Calculations for Each of the Three Wood Types.

Fastener Types		Head Embedment Stiffness (lbs./in.)		
		KD-19 Pine	Green Pine	Green Oak
Carriage Bolt	1/4 in.	32,391 (14.2)	32,060 (17.5)	49,845(12.2)
	3/8 in.	36,274 (16.3)	35,901 (16.3)	55,372 (19.5)
	1/2 in.	44,372 (15.3)	42,012 (15.3)	66,190 (12.9)
Lag Screws	1/4 in.	33,898 (15.2)	33,270 (20.7)	48,238 (13.4)
	3/8 in.	38,434 (11.9)	37,987 (16.0)	52,672 (17.1)
	1/2 in.	43,678 (13.2)	41,979 (19.2)	64,922 (13.4)

Values in parentheses are Coefficient of Variance values in percentages.

The Coefficient of Variances ranged from 11.9-20.7% for the head embedment stiffness. In the study published by Samarasinghe (1987) using nails the COV ranged from 18.6-28.5%. The lowest COV values were seen in the KD-19 pine, while the highest values were seen in the green pine. The previous nail study saw very high COV values in the green pine, and lower COV values in the green oak, which is similar to the findings shown in the table above. Similarly to the shank withdrawal stiffness values, as the fastener size increases, the head embedment stiffness value also increases. The head embedment stiffness values seen in the previous study using nails also showed larger head embedment stiffness values for the green oak samples compared to the green pine. The green pine and KD-19 pine head embedment stiffness values were very similar. A trend was observed that as size of the fastener increased, the head embedment stiffness value increased. The KD-19 pine values were all slightly higher than the stiffness values for green pine. The COV present in the KD-19 pine was lower than those seen in the green oak and green pine samples. The head embedment values for green oak seen during the Samarasinghe (1987) study had an average head embedment stiffness value of 42,557

lbs./in. for the nail type tested in green oak. The ¼ in. carriage bolts had an average head embedment stiffness of 49,845 lbs./in. in green oak. The ¼ in. lag screws had an average head embedment stiffness of 48,238 lbs./in. The ¼ in. carriage bolts in this study had a 17% higher head embedment stiffness in green oak than the nails used in Samarasinghe's (1987) study, and the ¼ in. lag screws were, on average, 14% stiffer than the nails used in that study. For green pine the average head embedment stiffness value reported in the Samarasinghe study was 23,400 lbs./in. In this study, the average head embedment stiffness value in green pine for ¼ in. carriage bolts was 32,060 lbs./in., and for ¼ in. lag screws was 33,270 lbs./in. The ¼ carriage bolt values were 37% larger than the average head embedment stiffness values for nails. The ¼ in. lag screws had a 42% larger average head embedment stiffness compared to the value for nails. To statistically evaluate the effect of wood species, fastener size, and fastener type on shank withdrawal stiffness, ANOVA tests were conducted. The predicted R² value for the ANOVA analysis was 0.71. All the variables present in Equation 10 were tested for significance. The effect of wood species ($p < 0.0001$) and fastener size ($p < 0.0001$) on the head embedment stiffness were significant. The fastener type and other interactions were determined not to be significant. The fastener type not being significant as a factor was unexpected for the head embedment test. The head of the fastener was held to the board with a washer in the lag screw connection, whereas in the carriage bolt connection the head of the bolt was embedded into the wood board. An explanation for this phenomenon may be that, when measured, the diameter of the washer and the diameter of the carriage bolt head were the same size, so this may have caused similar embedment patterns. Further analysis was run on the two significant interactions to understand those interactions more completely.

The other interactions that were run during the ANOVA analysis were not considered significant and further analysis was not run on those interactions. To further investigate the effect of the significant variables a Tukey HSD test was conducted. The results of the Tukey test for the wood species and fastener size are presented in **Tables 8-9**.

Table 8: Tukey's HSD Test for Head Embedment on the Three Wood Types

Level	Tukey Letter	Least Square Means
Green Oak	A	56234.35
KD-19 Pine	B	38174.575
Green Pine	B	37201.524

Note: Different capital letters represent statistically significant differences between the investigated levels.

Table 9: Tukey’s HSD Test for Head Embedment on Each of the Three Fastener Sizes

Level	Tukey Letter	Least Square Means
1/2	A	50525.551
3/8	B	42801.153
1/4	C	38283.744

Note: Different capital letters represent statistically significant differences between the investigated levels.

The Tukey’s analysis showed that the green pine and KD-19 pine samples were similar, while the green oak samples were significantly different from both pine types (**Table 8**). The green oak stiffness was 51% larger than the green pine stiffness, and 47% larger than the KD-19 pine. **Table 9** shows that the 0.5 in. fasteners were significantly different from the two smaller fasteners tested. Also, the 0.375 in. fasteners tested were shown to be different from the 0.25 in. fasteners. The 0.5 in. fasteners had a 32% greater stiffness than the 0.25 in. fasteners, and 18% greater stiffness compared to the 0.375 in. fasteners. The head embedment stiffnesses of the lag screws and carriage bolts were very similar and determined to not be significantly different from the ANOVA analysis. This is surprising considering the difference of the area under the head of the fasteners. The lag screws have a washer under their head, which creates a larger contact area with the

wood compared to carriage bolts which just have the head of the fastener contacting the wood. Further analysis would be needed to explain this phenomenon.

8.3 Edge Crushing Stiffness:

The calculated edge crushing stiffness values for the investigated alternative fasteners using the three wood species are presented in **Table 10**.

Table 10: Edge Crushing Stiffness Calculations for Each of the Three Wood Types

Fastener Types		Edge Crushing Stiffness (lbs./in.)		
		KD-19 Pine	Green Pine	Green Oak
Carriage Bolt	1/4 in.	14,593 (17.0)	14,196 (18.5)	22,446 (15.8)
	3/8 in.	17,580 (15.4)	17,030 (14.7)	26,162 (22.8)
	1/2 in.	21,712 (22.9)	21,272 (12.4)	30,465 (20.1)
Lag Screws	1/4 in.	15,677 (16.5)	15,162 (17.1)	22,901 (28.2)
	3/8 in.	18,692 (14.7)	18,208 (19.2)	27,422 (23)
	1/2 in.	22,014 (21.1)	21,688 (14.5)	32,010 (16.3)

Values in parentheses are Coefficient of Variance values in percentages.

The edge crushing stiffness was calculated using Equation 9 once the deckboard deflection was calculated using Equation 8. The Coefficient of Variance ranged from 12.4-28.2% for the edge crushing stiffness values. The COV published by Samarasinghe (1987) for nails reported greater values ranging from 36.4-48.5%. The green oak samples had the most variability seen in the COV values (16.3-22.8%) while the green pine had the lowest COV (12.4-19.2%). The green oak and green pine COV values in the previous study were both over 40% with the green pine being slightly larger at 48.5%. The stiffness values for green oak were larger than those seen for green pine in the previous study published by Samarasinghe (1987). The stiffness values seen for KD-19 pine were higher than the stiffness values seen in the green pine. The COV present in the KD-19

pine was lower than those seen in the green oak and green pine samples. The edge crushing stiffness for lag screws was larger than for carriage bolts for every wood type. The edge crushing stiffness reported for green pine pallet joints with nails in the Samarasinghe (1987) study, was on average 13,345 lbs./in. The ¼ in. carriage bolts used in green pine pallet joints in this study had an average stiffness value of 14,593 lbs./in. The ¼ in. lag screws used in green pine during this study had an average stiffness of 15,677 lbs./in. The ¼ in. carriage bolts were 6% stiffer than the nails used in the Samarasinghe (1987) study, and the ¼ in. lag screws were 17% stiffer compared to the nails from that study. The edge crushing stiffness reported for green oak pallet joints in the Samarasinghe (1987) study, was on average 20,450 lbs./in. The ¼ in. carriage bolts used in green pine in this study had an average stiffness value of 22,446 lbs./in. The ¼ in. lag screws used in green pine during this study had an average stiffness of 22,901 lbs./in. The ¼ in. carriage bolts are 9% stiffer than the nails used in Samarasinghe’s (1987) study, and the ¼ in. lag screws were 12% stiffer than the nails in that study. To statistically evaluate the effect of wood species, fastener size, and fastener type on the edge crushing stiffness, an ANOVA test was conducted. The predicted R² value for the ANOVA analysis was 0.78. The effects of wood species (p < 0.0001), fastener size (p < 0.0001), and fastener type (p < 0.0369) on the edge crushing stiffness values were significant. The other interactions tested for in the ANOVA analysis were seen as not significant, so further analysis was not run on these interactions.

To further investigate the effect of the significant variables a Tukey’s HSD test was conducted. The results of the Tukey test for wood species, fastener size, and fastener type are presented in **Tables 11-13**.

Table 11: Tukey’s HSD Test for Moment Rotation on the Three Wood Types

Level	Tukey Letter	Least Square Means
Green Oak	A	27116.435

KD-19		
Pine	B	18542.431
Green Pine	B	18075.52

Note: Different capital letters represent statistically significant differences between the investigated levels.

Table 12: Tukey’s HSD Test for Edge Crushing Stiffness on each of the three fastener sizes

Level	Tukey Letter	Least Square Means
1/2	A	25083.203
3/8	B	20969.724
1/4	C	17681.458

Note: Different capital letters represent statistically significant differences between the investigated levels.

Table 13: Tukey’s HSD Test for Edge Crushing Stiffness on Each of the Fastener Types

Level	Tukey Letter	Least Square Means
Lag Screw	A	21693.083
Carriage Bolt	B	20796.505

Note: Different capital letters represent statistically significant differences between the investigated levels.

The Tukey's test results (**Table 11**) shows that the green oak samples were significantly different than the green and KD-19 pine samples that were tested. The green and KD-19 pine samples were shown to be similar through that test. The green oak samples had a 50% greater stiffness compared to the green pine samples and a 45% greater stiffness compared to the KD-19 pine. The Tukey's HSD test that was performed to determine the significance of fastener size (**Table 12**) showed that the three sizes of fasteners were all significantly different from one another. The 0.5 in. fasteners had a 42% greater stiffness than the 0.25 in. fasteners and a 20% greater stiffness than the 0.375 in. fasteners. The two types of fasteners were shown to be significantly different with a p-value of 0.369 (**Table 13**). Using lag screws resulted in 4% higher edge crush stiffness values than when using carriage bolts.

8.4 Model Creation

8.4.1 Shank Withdrawal Stiffness Models

Figure 13 shows the correlation between wood's specific gravity and the shank withdrawal stiffness of pallet joints made with the alternative fasteners. The model shows a strong correlation between specific gravity and shank withdrawal stiffness ($R^2=0.79$). A similar model was created in the previous study done by Samarasinghe (1987) in which they predicted the shank withdrawal stiffness of pallet joints using nails.

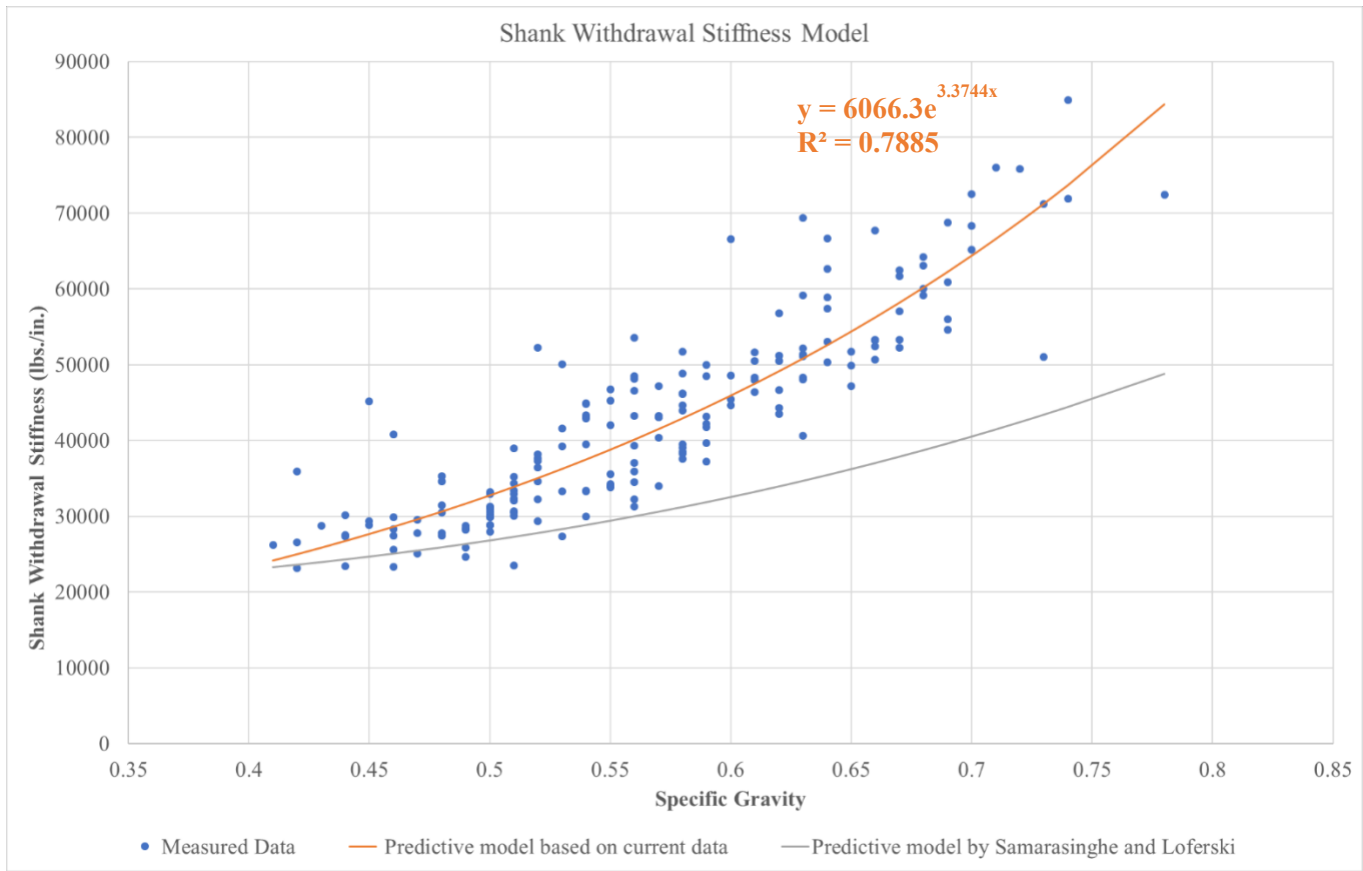


Figure 13: The predictive model between specific gravity and shank withdrawal stiffness measured for pallet joint made with different alternative fasteners vs. nails pallet joints investigated by Samarasinghe (1987).

Figure 13 shows that the two models produced similar results for the lower end of the specific gravity values. But, as the specific gravity increases, the model developed by Samarasinghe (1987) for nails underestimates the shank withdrawal stiffness values for the alternative fasteners investigated in the current study by as much as 41%. The difference between the two models could be explained by the different types of fasteners investigated in the two studies. The smaller alternative fasteners investigated in the current study behave closer to the nails in the previous study, while the larger alternative fasteners seem to differ significantly.

However, to investigate the effect of individual fasteners, the correlation between specific gravity and shank withdrawal stiffness is presented for each of the different types and sizes of fasteners (**Figures 14-19**). The stiffness values were plotted on six individual

graphs, one for each unique fastener type and size tested, with specific gravity as the independent variable. A linear trendline was created to acquire an equation for each dataset that could predict the stiffness values using just the specific gravity. As long as the wood species being used is between the specific gravity range of 0.41 to 0.78, the equations below can be used to predict the shank withdrawal stiffness expected from each of the six fasteners when using these different wood species.

The model for 0.375 in. carriage bolt shank withdrawal, which is plotted in **Figure 16** with an R^2 value of 0.8609, had the highest correlation to the measured data.

The model for 0.5 in. lag screws, which is plotted in **Figure 19** with an R^2 value of 0.6479, had the lowest correlation to the measured data.

All the figures show that shank withdrawal stiffness is positively correlated with the blocks' specific gravities. The green oak samples had the highest stiffness values for shank withdrawal; they also had a higher specific gravity than the green and KD-19 pine samples tested. This was found to be true in the nail study as well; the green oak samples had much higher values compared to the green pine.

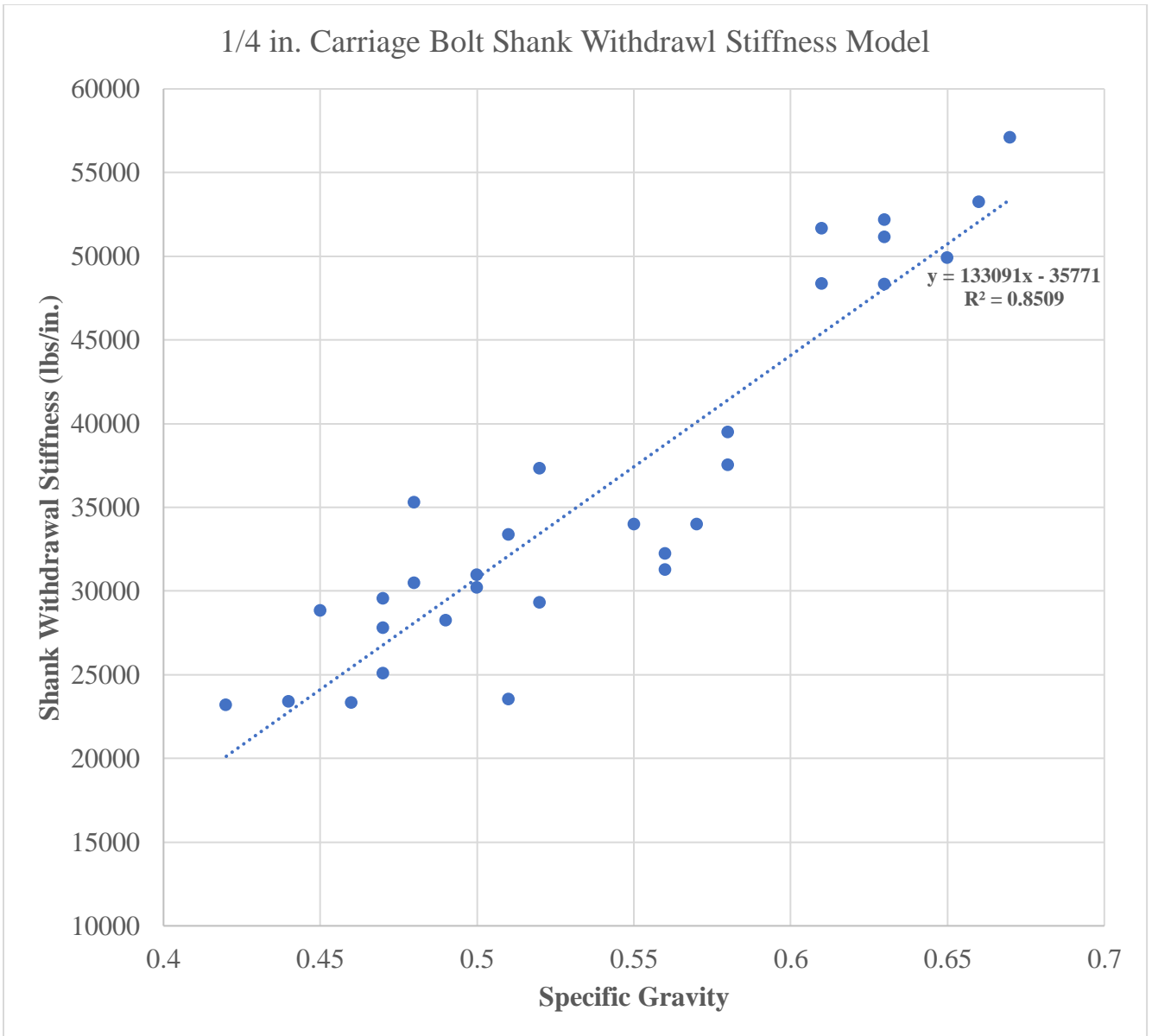


Figure 14: Correlation between the 0.25 in. carriage bolt shank withdrawal stiffness and pallet block specific gravity.

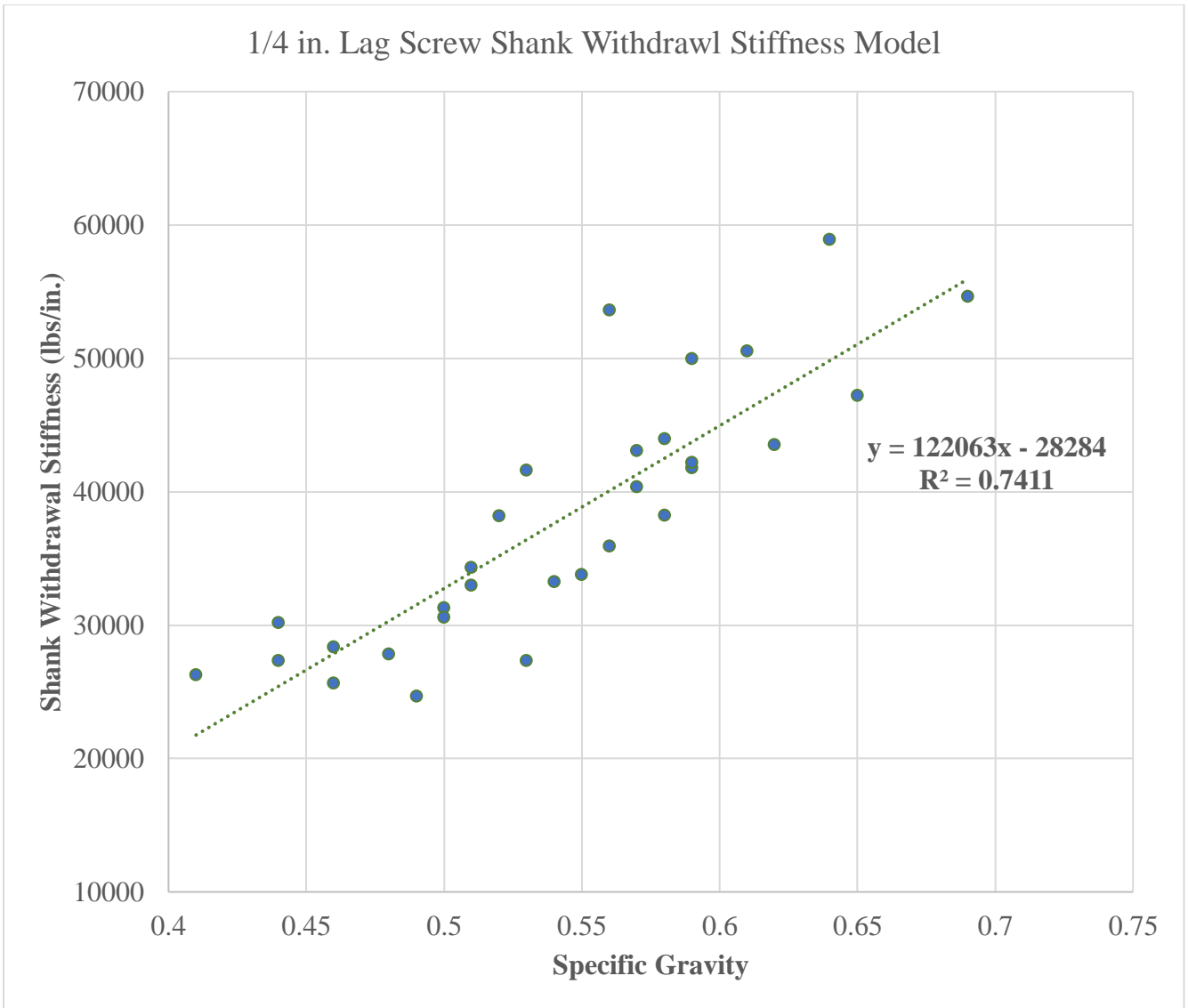


Figure 15: Correlation between the 0.25 in. lag screw shank withdrawal stiffness and pallet block specific gravity.

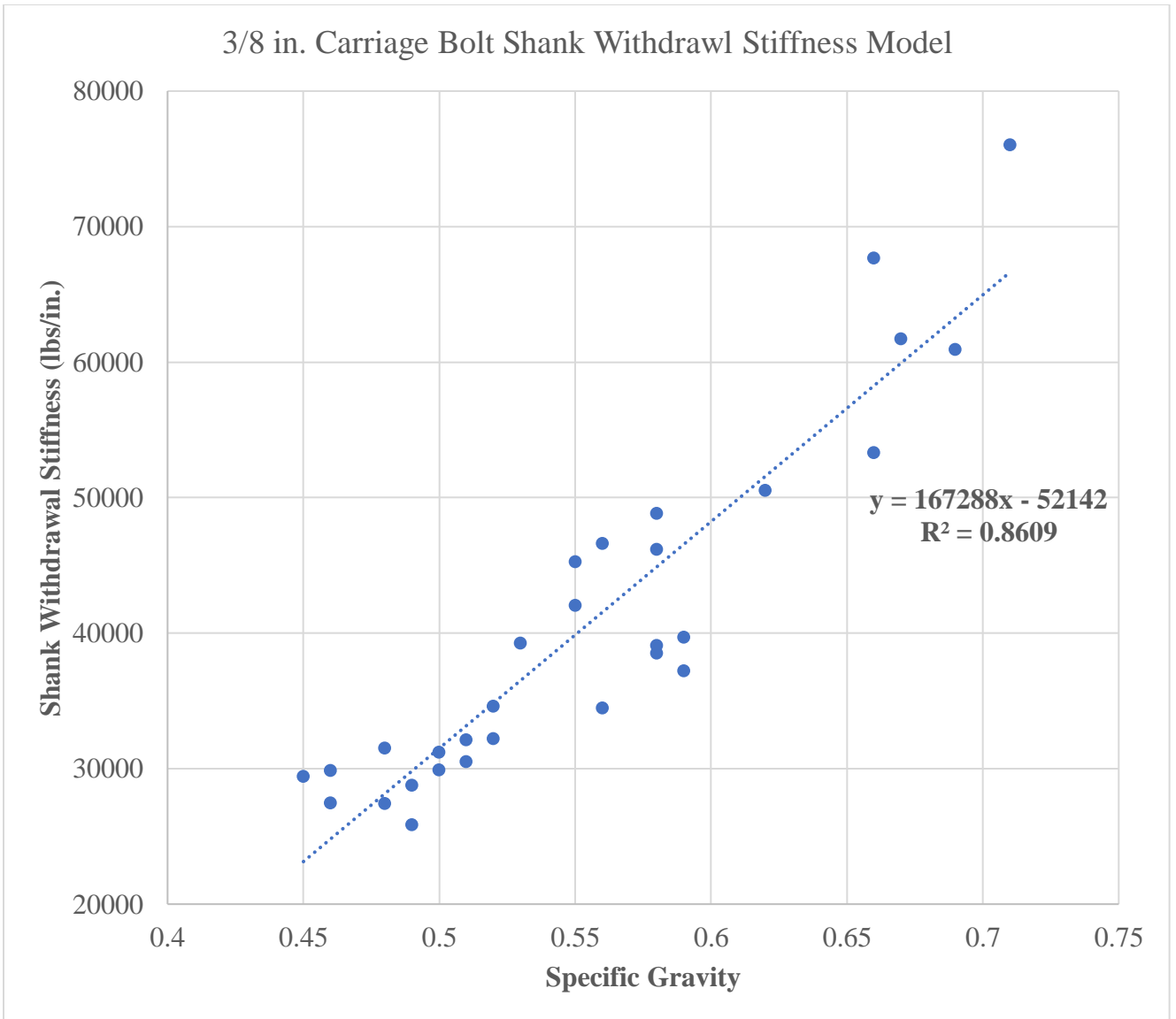


Figure 16: Correlation between the 0.375 in. carriage bolt shank withdrawal stiffness and pallet block specific gravity.

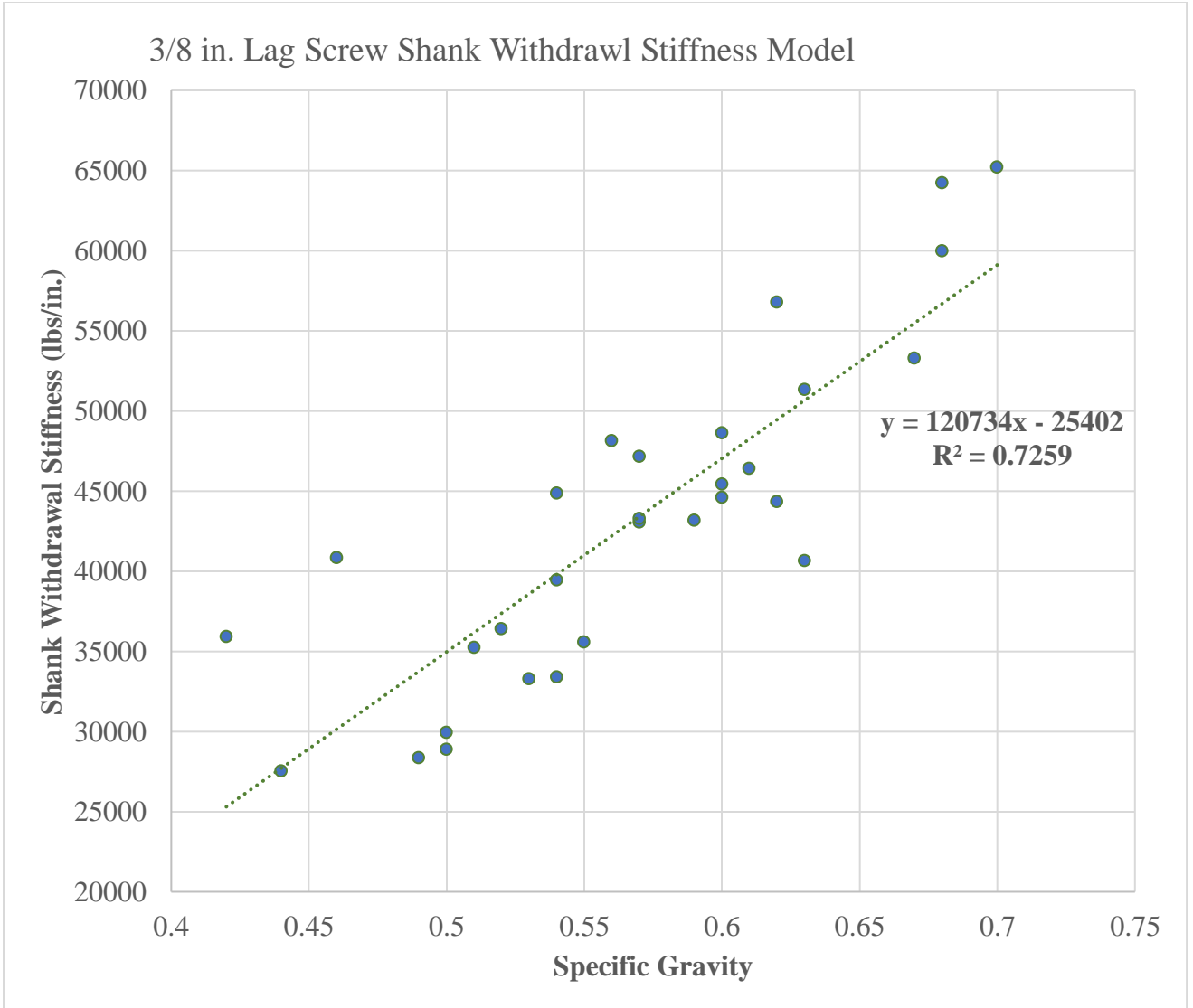


Figure 17: Correlation between the 0.375 in. lag screw shank withdrawal stiffness and pallet block specific gravity.

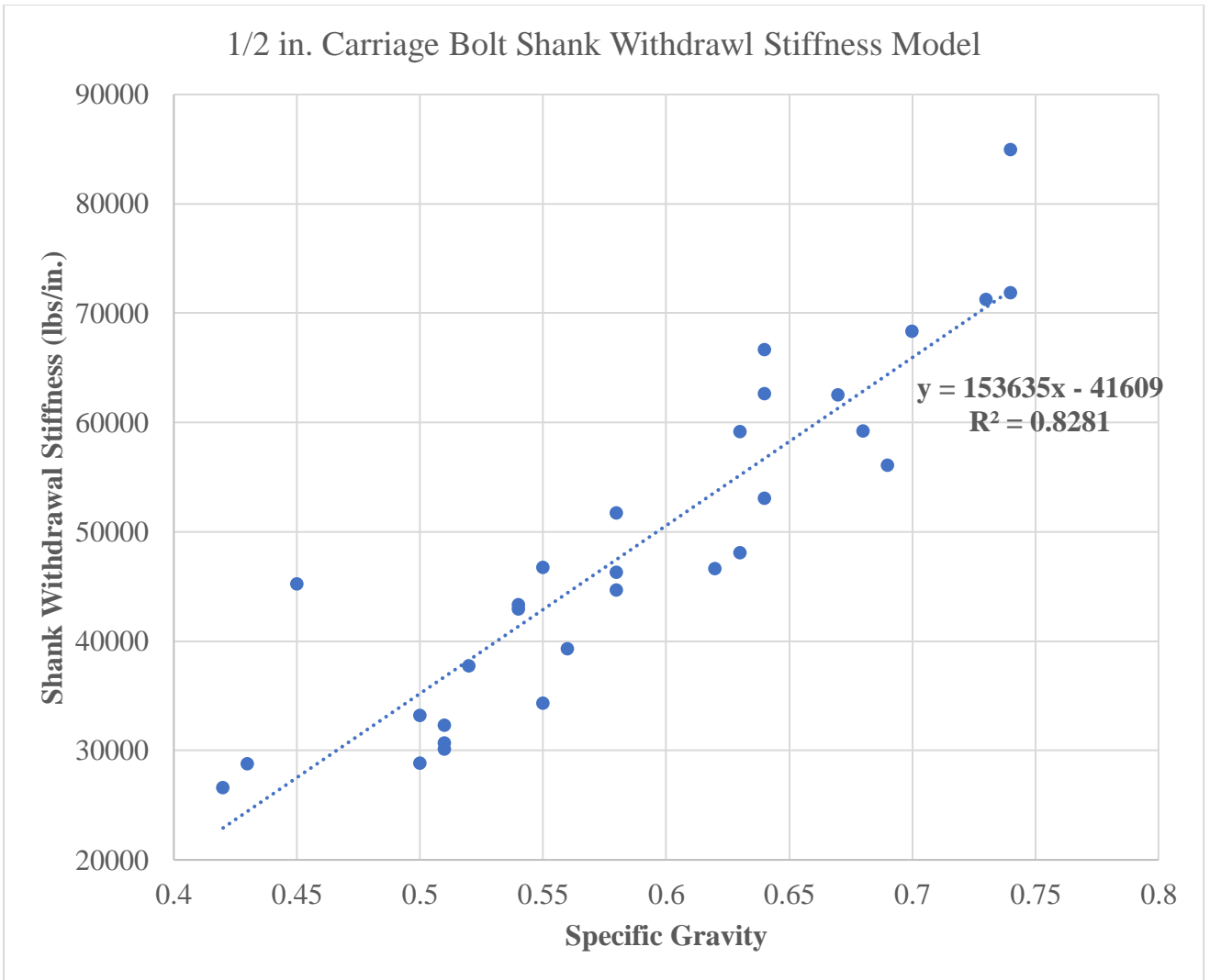


Figure 18: Correlation between the 0.5 in. carriage bolt shank withdrawal stiffness and pallet block specific gravity

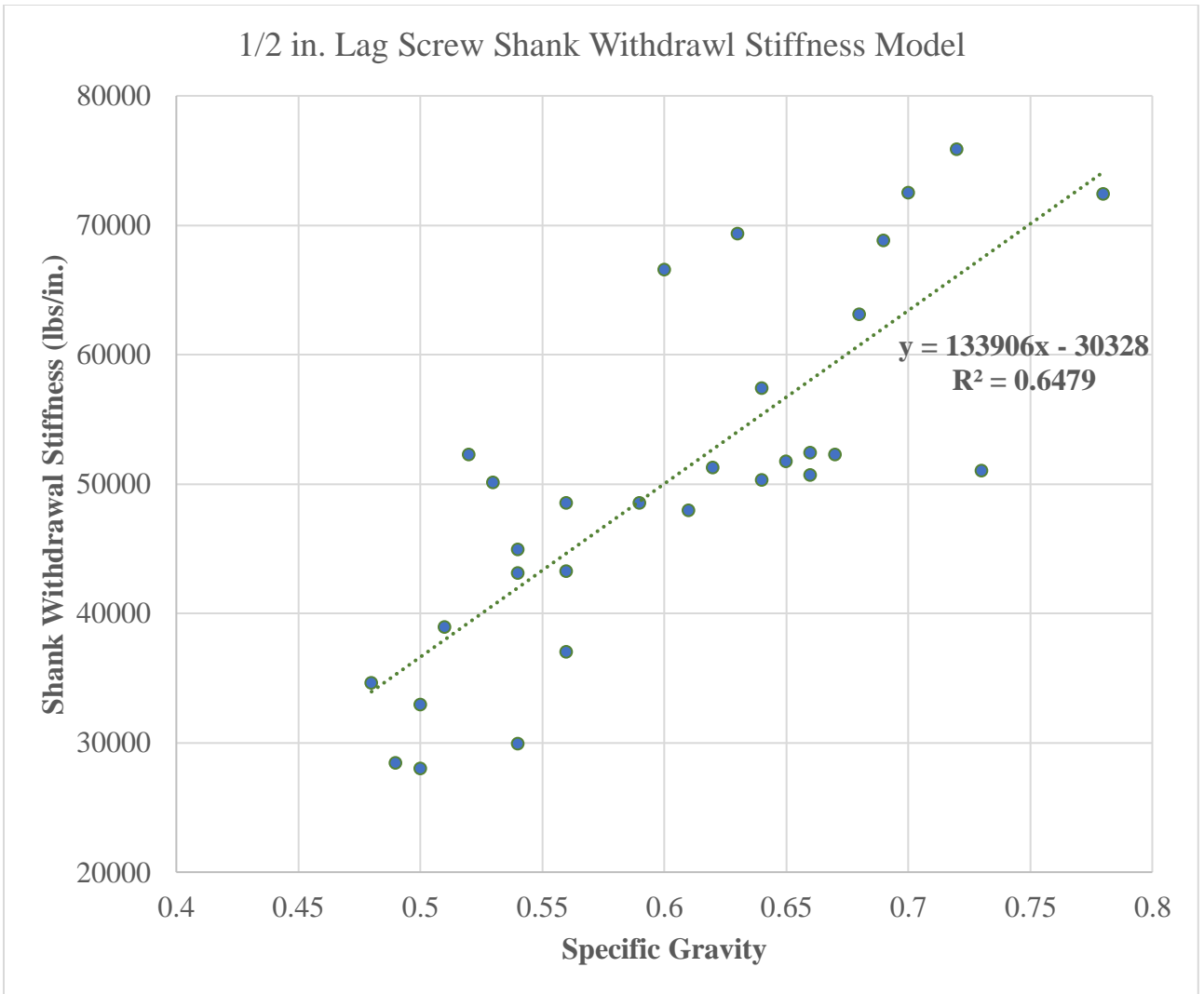


Figure 19: Correlation between the 0.5 in. lag screw shank withdrawal stiffness and pallet block specific gravity.

8.4.2 Head Embedment Stiffness Models

The correlation between woods' specific gravity and the head embedment stiffness of the pallet joints made with different alternative fasteners is presented in **Figure 20**. The model shows a strong correlation between specific gravities and head embedment stiffness ($R^2=0.69$). A similar formula was created in the previous work done by Samarasinghe, where they predicted the head embedment stiffness that would occur in pallet joints using nails.

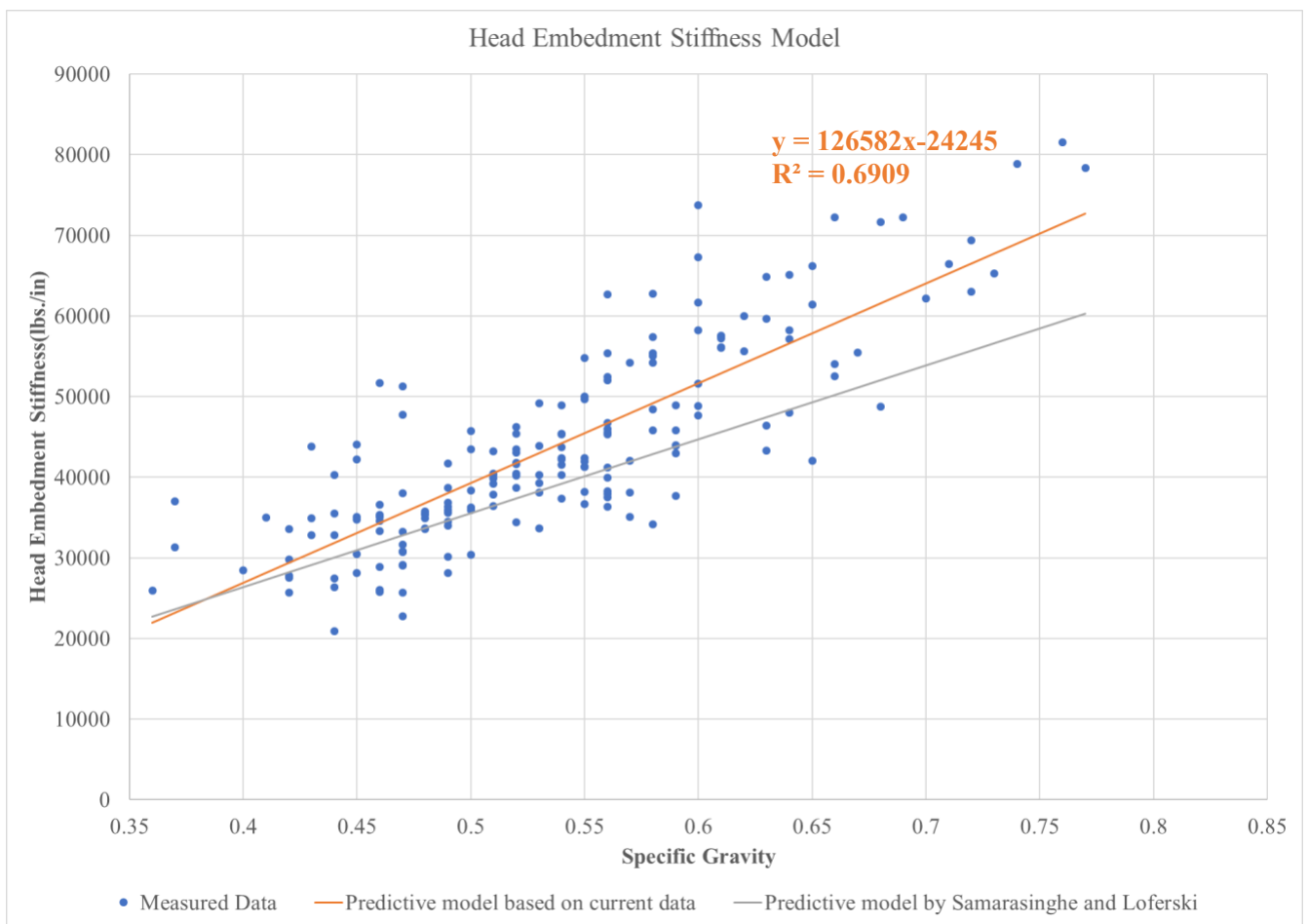


Figure 20: The predictive model between specific gravity and head embedment stiffness measured for pallet joint made with different alternative fasteners vs. nails pallet joints investigated by Samarasinghe (1987).

Figure 20 shows that the two models produce similar results for the lower end of the specific gravity values. However, as the specific gravity increases, the model

developed by Samarasinghe (1987) for nails underestimates the head embedment stiffness values for the alternative fasteners investigated in the current study by as much as 34%. The difference between the two models could be explained by the different types of fasteners investigated in the two studies. The smaller alternative fasteners investigated in the current study behave closely to nails, but the larger fasteners seem to differ significantly.

To investigate the effect of individual fasteners, the correlation between specific gravity and head embedment stiffness was presented for each of the different types and sizes of fasteners (**Figures 21-26**). The stiffness values were plotted on six individual graphs, one for each unique fastener type and size tested, with specific gravity as the independent variable. A linear trendline was created to acquire an equation for each dataset that could be used to predict the stiffness values using just specific gravity. As long as the wood species being used is between the specific gravity range of 0.36 to 0.77, the equations shown below can be used to predict the head embedment stiffness expected from each of the six fasteners when using the different wood species.

The model for 0.25 in. carriage bolt shank withdrawal, which is plotted in **Figure 21** with an R^2 value of 0.7302, was the highest correlation to the measured data.

The model for 0.375 in. lag screw shank withdrawal, which is plotted in **Figure 24** with an R^2 value of 0.6263, had the lowest correlation to the measured data.

All of the figures show that the head embedment stiffness is positively correlated with deckboards' specific gravities. The green oak samples had the highest stiffness values for head embedment. The green oak samples also had a higher specific gravity than both the green and KD-19 pine samples. This was true in the nail study as well; the green oak samples had much higher values compared to the green pine.

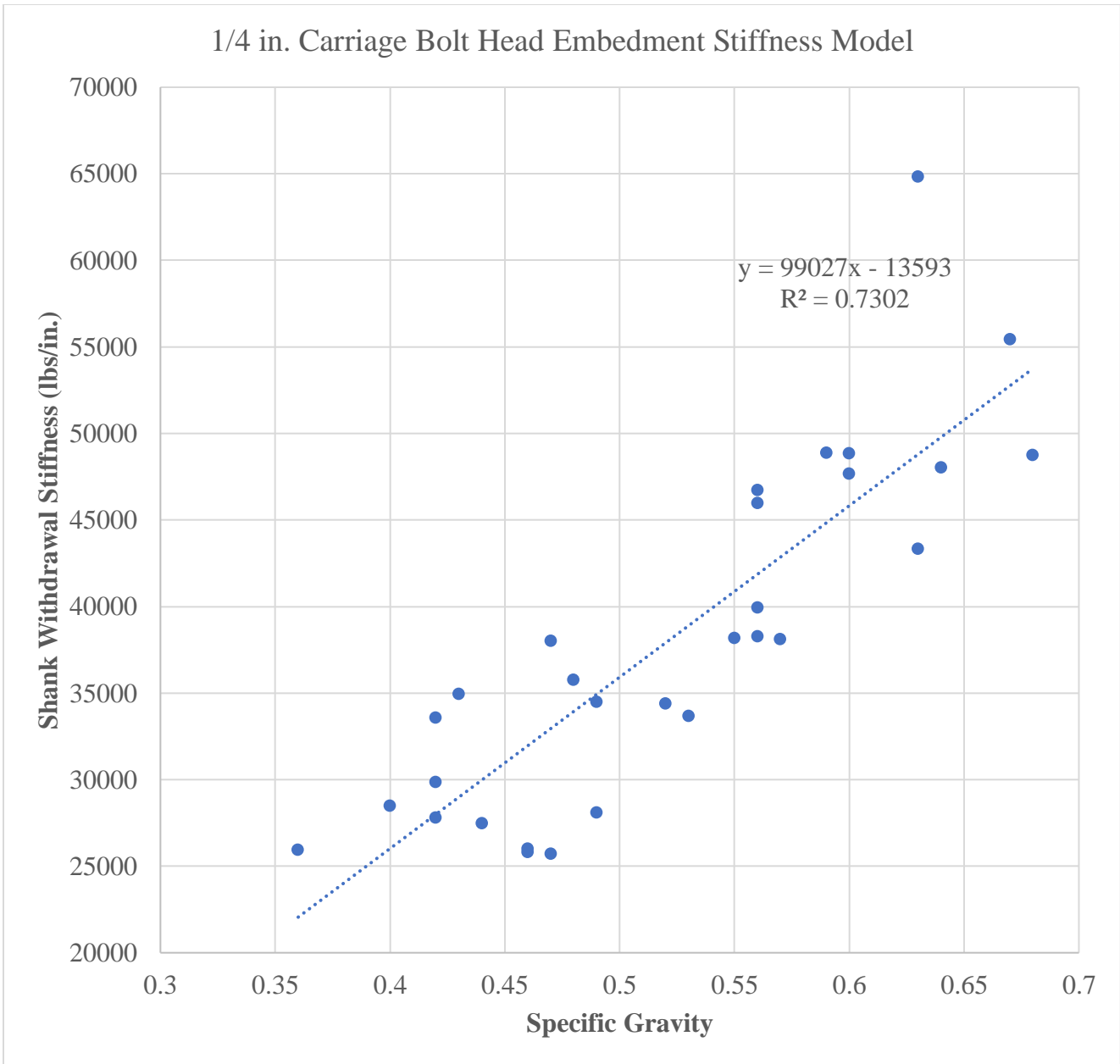


Figure 21: Correlation between the 0.25 in. carriage bolt head embedment stiffness and pallet board specific gravity.

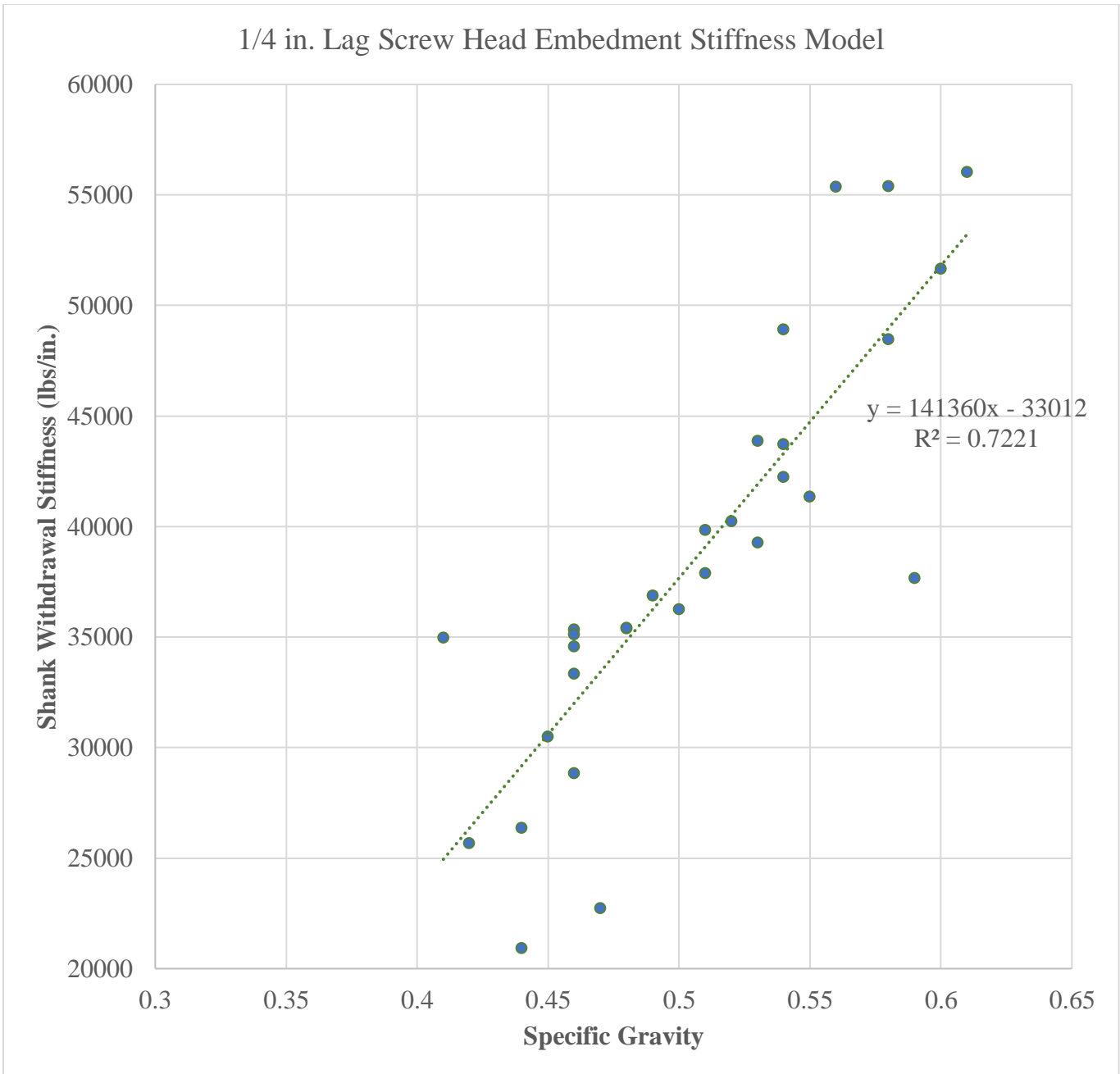


Figure 22: Correlation between the 0.25 in. lag screw head embedment stiffness and pallet board specific gravity.

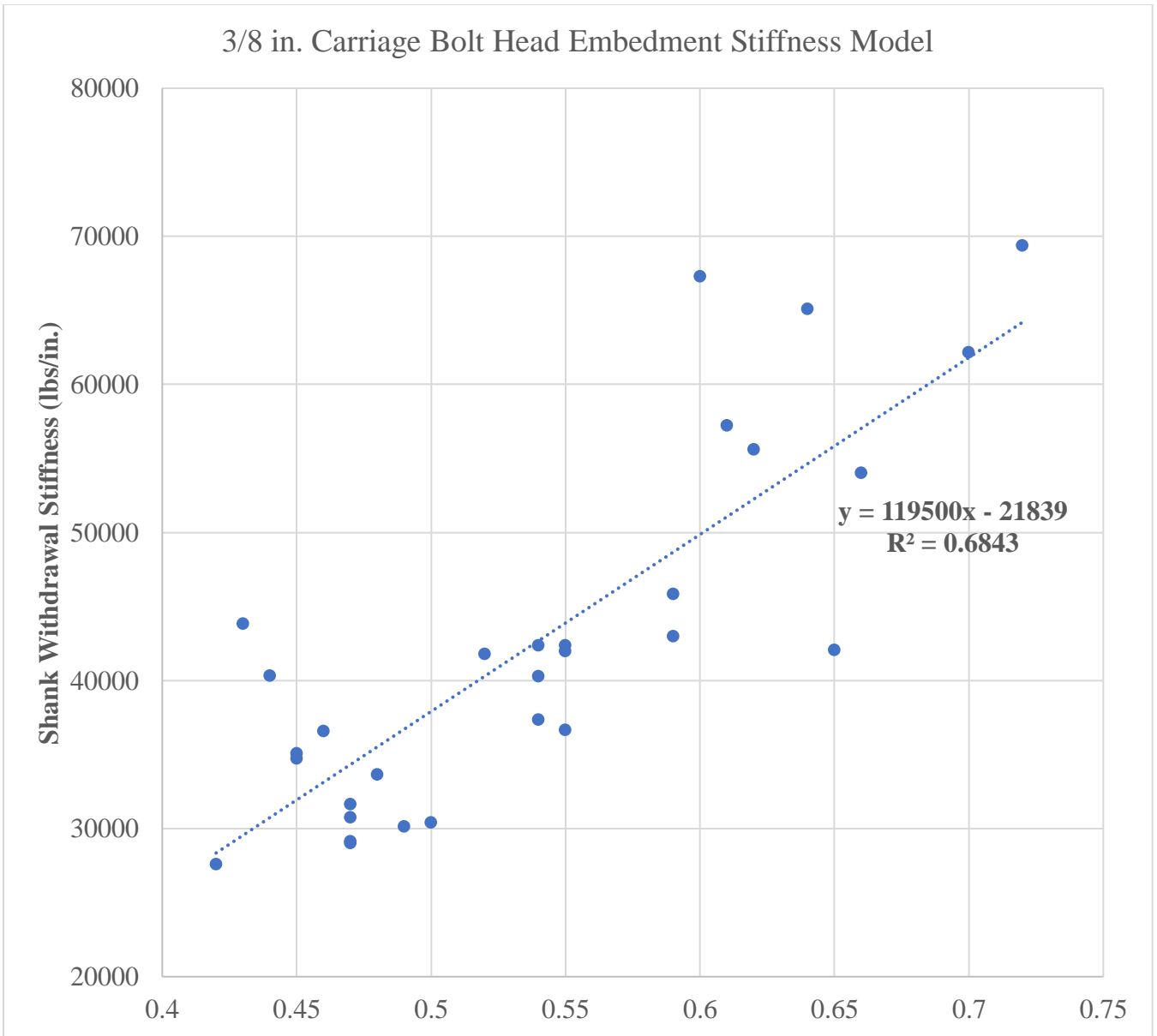


Figure 23: Correlation between the 0.375 in. carriage bolt head embedment stiffness and pallet board specific gravity.

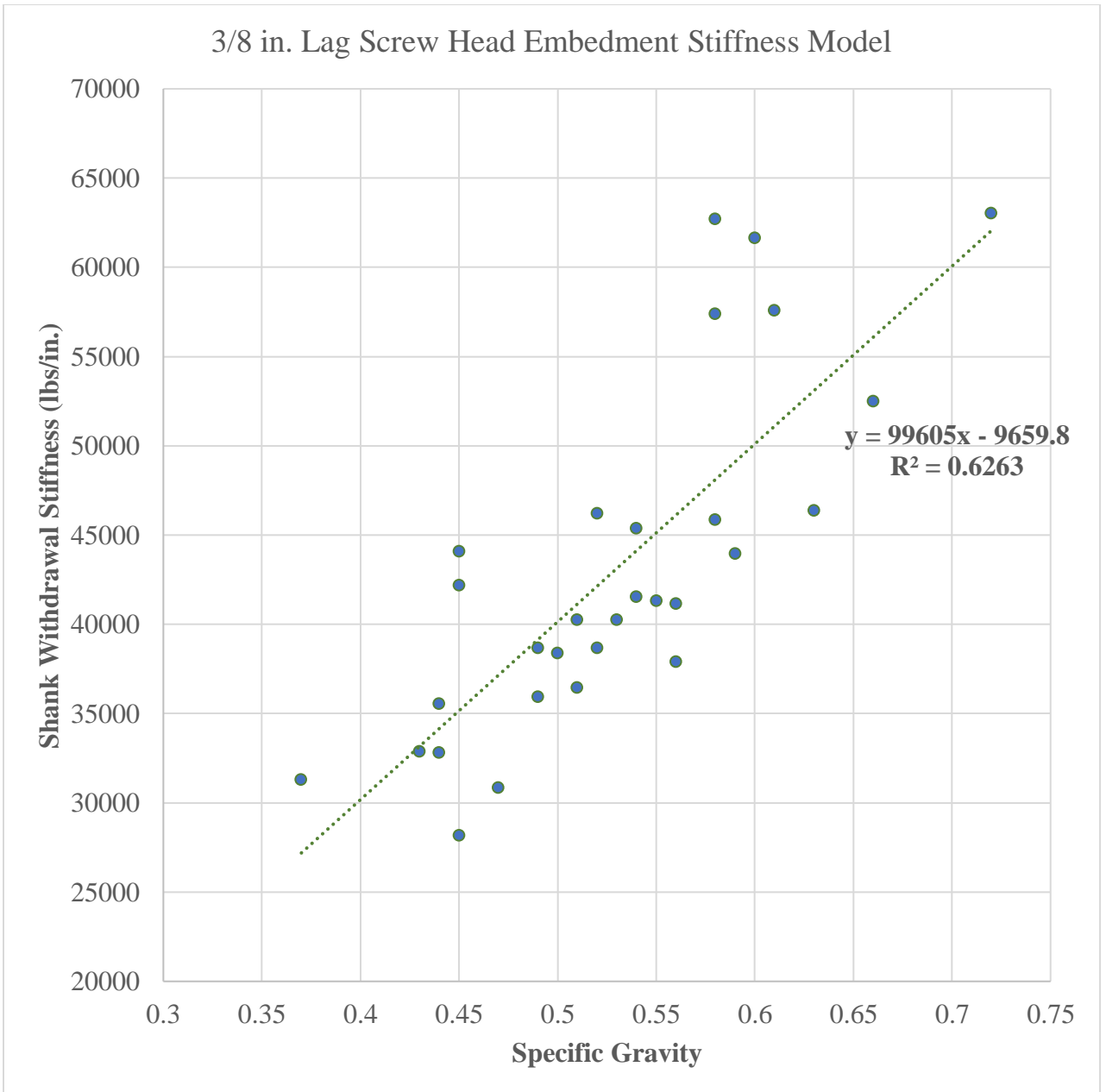


Figure 24: Correlation between the 0.375 in. lag screw head embedment stiffness and pallet board specific gravity.

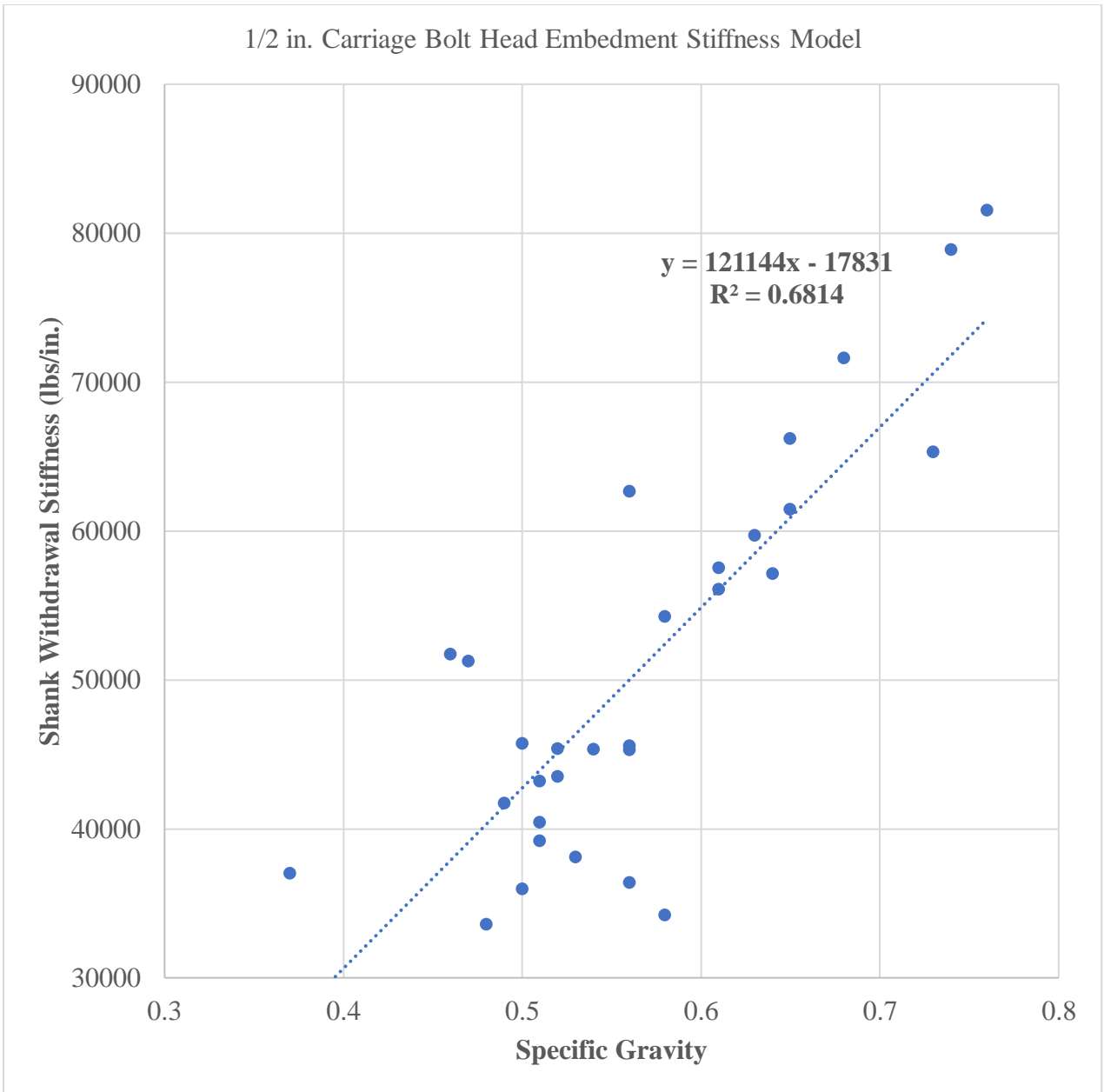


Figure 25: Correlation between the 0.5 in. carriage bolt head embedment stiffness and pallet board specific gravity.

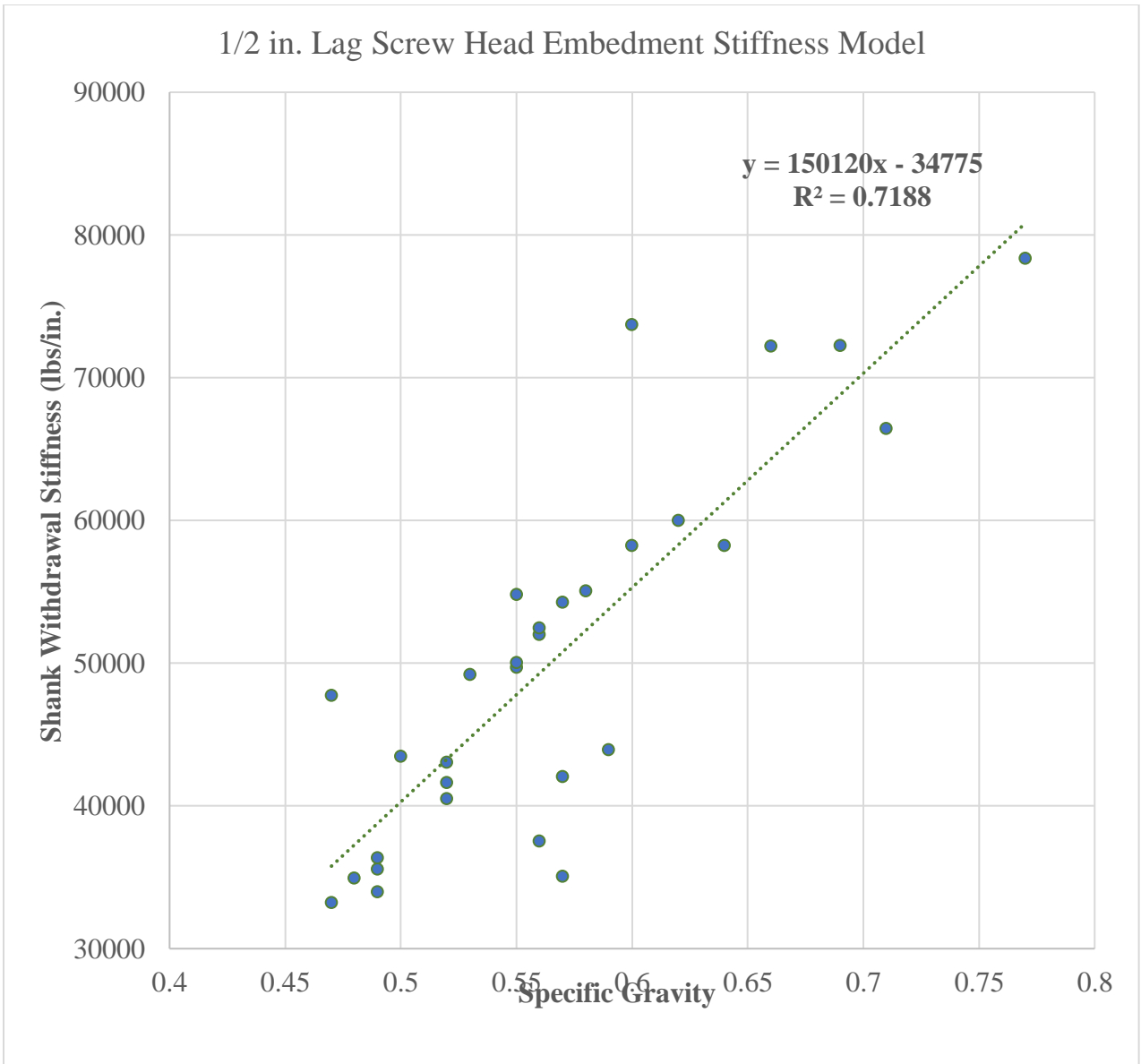


Figure 26: Correlation between the 0.5 in. lag screw head embedment stiffness and pallet board specific gravity.

8.4.3 Edge Crushing Model

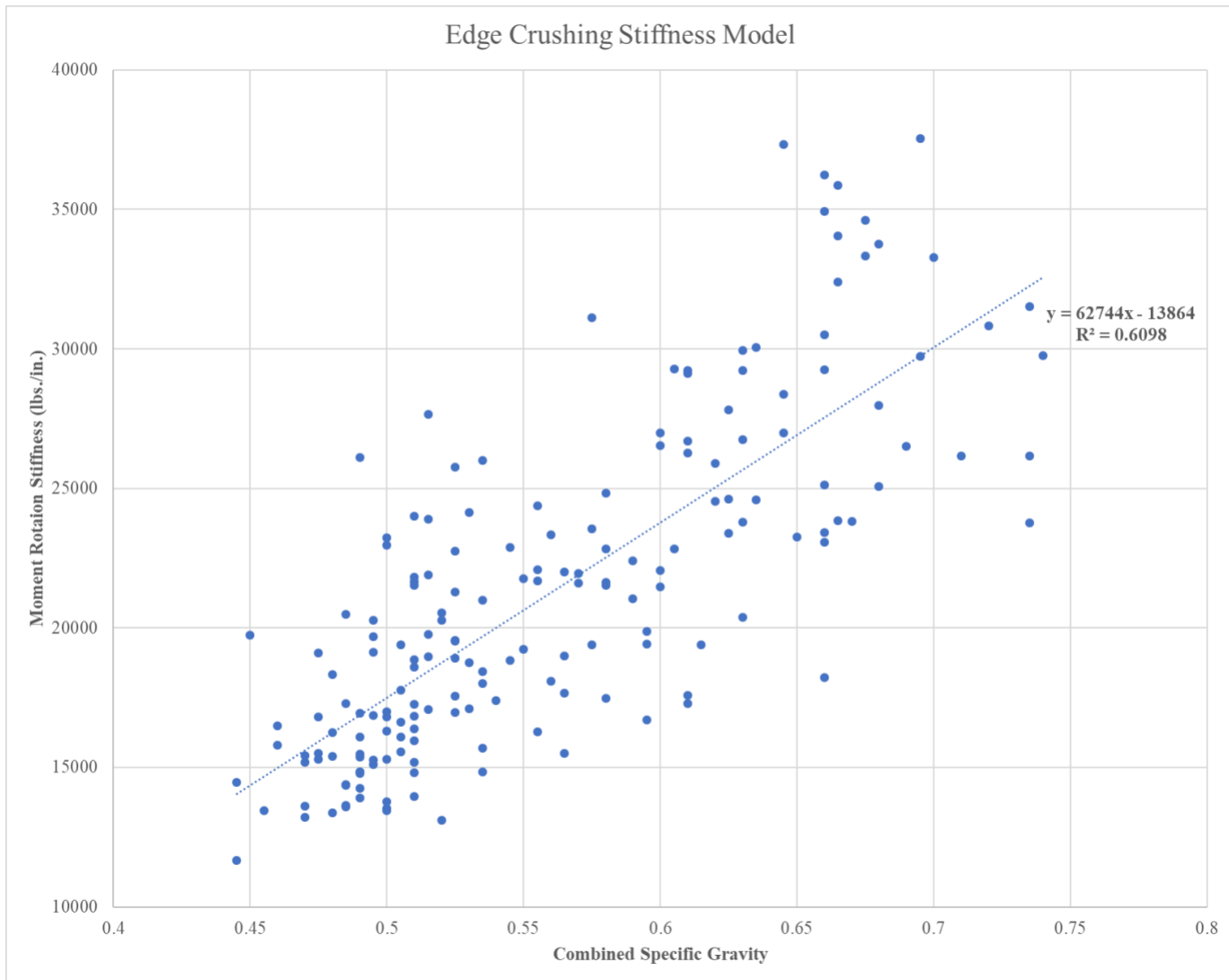


Figure 25: The predictive model between combined block and board specific gravities and edge crushing stiffness values measured for pallet joints made with different alternative fasteners.

The final model developed was to predict the edge crushing stiffness using the specific gravity of the wood. The specific gravities of the board and the block were averaged together and the resulting average specific gravity was correlated to the edge crushing stiffness using a linear regression. The correlation between edge crushing stiffness and the average specific gravities was strong with an R^2 value of 0.6098 (**Figure 25**).

A linear trendline was created to acquire an equation for each dataset that could predict the stiffness values using just the specific gravities. As long as the wood species being used is between the specific gravity range of 0.44 to 0.74, the equation can be used to predict the edge crushing stiffness expected from each of the six fasteners in the different wood species.

Figure 25 shows that edge crushing stiffness is positively correlated to specific gravity. The green oak samples had the highest stiffness values for edge crushing. The green oak samples also had a higher specific gravity than the green pine and KD-19 pine samples. This was true in the nail study as well; the green oak samples had much higher values compared to the green pine.

8.4.4 Shank Withdrawal Stiffness Multivariate Model

During shank withdrawal, the carriage bolts behaved similar to the head embedment testing; thus, only the shank withdrawal of the lag screws was investigated using a multivariate regression model. The multivariate linear regression model was conducted using JASP (2018) statistical software using size and specific gravity as the independent variables. The model had an R^2 value of 0.746. This value is similar to the model that was created based just on the specific gravities. The interactions between the variables were not significant. Equation 13, produced for the model, is below:

$$y = 19252.6\alpha + 126572.63\beta - 35702.29 + \varepsilon \quad (\text{Equation 13})$$

α = Fastener Size

β = Block Specific Gravity

Table 14: Predicted Shank Withdrawal Stiffness Calculations for each Fastener Type

Fastener Types		KD-19 Pine					Green Pine					Green Oak				
		Size (in.)	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Size (in.)	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Size (in.)	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)
Lag Screws	1/4 in.	0.25	0.51	33,270	33789	-2	0.25	0.51	32,641	33030	-1	0.25	0.61	40,564	46447	-13
	3/8 in.	0.375	0.51	37,987	36449	4	0.375	0.56	37,902	42272	-10	0.375	0.63	48,564	51511	-6
	1/2 in.	0.5	0.53	41,979	40754	3	0.5	0.60	41,352	49614	-17	0.5	0.68	60,564	60500	0

$$y = 19252.6\alpha + 126572.63\beta - 35702.29 + \varepsilon$$

$$R^2 = 0.746$$

Table 14 shows the stiffnesses measured during shank withdrawal testing compared to the predicted model for the shank withdrawal stiffness based on specific gravity and fastener type using **Equation 13**. The error percentage associated with the measured vs. predicted stiffness is also provided. For both the green oak and KD-19 pine, the model predicts the stiffness within a 13% error. For the green pine samples, there were two fastener types that the model did not predict as well for with a 10% and 17% error. One reason for this may be the small number of samples; there were only ten blocks tested for each wood/fastener combination. This may not have created enough data to reliably use the model. The model also underpredicted the values for certain fasteners so having wood samples with a wider range of specific gravities could help. One limitation of this study is that the model can only predict within the specific gravity range of 0.51-0.68.

8.4.5 Head Embedment Stiffness Multivariate Model

The carriage bolts from the shank withdrawal testing behaved similar to the head embedment testing; thus, those results were included in the model with the head embedment data. The multivariate linear regression model was created in JASP (2018) statistical software using specific gravity and bearing area as independent variables. The bearing area was selected as an independent variable instead of the size of the fasteners because the bearing area is a more quantifiable property that affects head embedment performance. The model that was created produced an R^2 value of 0.749. This value is better than the linear model created using just the specific gravity. If the bearing areas differed more between the carriage bolts and lag screws, this model could prove to be more useful. The interactions between the variables were not significant. Equation 14, produced for this model, is below:

$$y = 10650.53\alpha + 125212.92\beta - 38865.96 + \varepsilon \quad (\text{Equation 14})$$

α = Bearing Area

β = Board Specific Gravity

Table 15: Predicted Head Embedment Stiffness Calculations for each Fastener Type

Fastener Types		KD-19 Pine					Green Pine					Green Oak				
		Board SG	Bearing Area (in.)	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Board SG	Bearing Area (in.)	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Board SG	Bearing Area (in.)	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)
Carriage Bolt Top	1/4 in.	0.48	0.986	32391	31487	3	0.47	0.986	32060	30736	4	0.63	0.986	49845	48767	2
	3/8 in.	0.51	1.228	36274	37821	-4	0.48	1.228	35901	34440	4	0.63	1.228	55372	52847	5
	1/2 in.	0.55	1.581	44372	46214	-4	0.49	1.581	42012	39452	6	0.65	1.581	66190	61239	8
Lag Screws	1/4 in.	0.44	1.052	33898	31564	7	0.48	1.052	33270	31940	4	0.57	1.052	48238	43459	11
	3/8 in.	0.5	1.294	38434	37272	3	0.47	1.294	37987	35769	6	0.6	1.294	52672	50419	4
	1/2 in.	0.53	1.655	43678	45374	-4	0.52	1.655	41979	44372	-5	0.64	1.655	64922	59147	10
Carriage Bolt Bottom	1/4 in.	0.50	0.986	32,060.00	34492	-7	0.50	0.986	28855	33866	-15	0.62	0.986	37234	49142	-24
	3/8 in.	0.53	1.228	35901	39950	-10	0.51	1.228	33050	38071	-13	0.63	1.228	44234	52847	-16
	1/2 in.	0.56	1.581	42012	47967	-12	0.51	1.581	38592	42207	-9	0.69	1.581	68234	63869	7

$$y = 10650.53\alpha + 125212.92\beta - 38865.96 + \varepsilon$$

$$R^2 = 0.745$$

Table 15 shows the predicted head embedment stiffness as it compares to the measured values. It also provides the error percentage associated with the prediction vs. the actual measured value. The prediction model for the head embedment stiffness is based on specific gravity and the bearing area under the fastener head using **Equation 14**. The predictive ability of the model was stronger for the top head embedment of carriage bolts, as well as lag screws, rather than the bottom embedment of the carriage bolts. A lack of samples could be reason for this discrepancy; the shank withdrawal model had a similar shortcoming.

For both the green oak and KD-19 pine, the model predicts the stiffness within a 13% error. For the green pine samples, there were two fastener types that the model did not predict as well for with a 10% and 17% error. One reason for this may be the small number of samples; there were only ten blocks tested for each wood/fastener combination. This may not have created enough data to reliably use the model. The model also underpredicted the values for certain fasteners so having wood samples with a wider range of specific gravities could help. One limitation of this study was that the model can only predict within the specific gravity range of 0.51-0.68.

8.4.6 Moment Rotation Testing Multivariate Model

The multivariate linear model was created in JASP (2018) statistical software using block specific gravity and board specific gravity as independent variables. Equation 15 was derived from running the model. The model that was created produced an R^2 value of 0.469. The model created by Samarasinghe (1987) had an R^2 value of 0.54 which was slightly better than the one from the current study, but it is still low. The reason for this low R^2 value could be due to the fact that there are other factors that need to be accounted for that this model does not take into consideration. An example is the effect of the block's specific gravity versus the board's specific gravity. The model accounts for both of these equally; however, one specific gravity definitely could affect the joint more than the other.

$$y = 36269.17\alpha + 17209.01\beta - 8482.46 + \varepsilon \quad (\text{Equation 15})$$

α = Board Specific Gravity

β = Block Specific Gravity

Table 16: Predicted Edge Crushing Stiffness Calculations for each Fastener Type

Fastener Types		KD-19 Pine					Green Pine					Green Oak				
		Board SG	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Board SG	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)	Board SG	Block SG	Measured Stiffness (lbs./in.)	Predicted Stiffness (lbs./in.)	Error (%)
Carriage Bolt	1/4 in.	0.48	0.48	14759.77	17493.13	-16	0.47	0.52	14252.24	14189.47	1	0.63	0.64	23031.73	24511.73	-6
	3/8 in.	0.51	0.52	17673.07	18977.01	-7	0.48	0.49	17197.07	17739.6	-3	0.63	0.68	26265.9	25101.84	5
	1/2 in.	0.55	0.51	21909.64	20904.07	5	0.49	0.51	21436.85	19153.92	12	0.65	0.64	30642.29	27441.92	12
Lag Screws	1/4 in.	0.44	0.52	15776.81	17363.4	-9	0.48	0.51	15287.96	15575.47	-2	0.57	0.65	22980.24	22633.13	2
	3/8 in.	0.5	0.56	18863.55	19199.42	-2	0.47	0.54	18372.9	17972.58	2	0.6	0.68	27445.85	24263.94	13
	1/2 in.	0.53	0.54	22271.75	21103.73	6	0.52	0.53	21906.09	19608.94	12	0.64	0.66	32332.58	26573.31	22

Note: Equation used to predict stiffness: $y = 36269.17\alpha + 17209.01\beta - 8482.46 + \varepsilon$ ($R^2 = 0.469$)

Table 16 shows the predicted edge crushing stiffness values as they compare to the measured edge crushing stiffness values. The table also provides the error percentage associated with the predictions versus the actual measured values. The prediction model for edge crushing stiffness is based on block and board specific gravity using **Equation 15**. The predictive ability of the model was stronger for the smaller fasteners. As the size of fastener and edge crushing stiffness values increased, the prediction errors were higher. A lack of samples could be reason for this discrepancy.

The model predicted well for both the green pine and KD-19 pine. However, for the oak samples, the model seems to underpredict the stiffness values as the alternative fastener sizes increased. For lag screws the 0.25 in. size had a 2% error, the 0.375 in. size had a 13% error, and the 0.5 in. size had a 22% error. As the size increased the error percentage increased as well. A lack of samples could be reason for this disparity.

9 Conclusions

The key findings of the present study investigating the effect of alternative fasteners (carriage bolts and lag screws) on the stiffness values of pallet joints are presented below:

- The stiffnesses of pallet joints using the smallest (.25 in.) alternative fasteners were found to be 6-42% greater than what was observed for nailed connections.
- With the increase in size of the investigated alternative fasteners, all of the three investigated pallet joint stiffness values increased.
- There is an increase in all of the investigated pallet joint stiffnesses when the wood type changed from green or KD-19 pine to green oak.
- There is not a significant difference in the head embedment stiffness of lag screws and carriage bolts. The lack of difference between the two investigated fasteners can be explained by the nearly identical fastener bearing area under the heads of the two fasteners.
- Due to the greater stiffness values observed for the alternative fasteners, the predictive models built by Samarasinghe continuously underpredicted the stiffness of the pallet joints using the alternative fasteners.
- The correlation between the woods' specific gravity and the head embedment and shank withdrawal stiffnesses were strong with 0.6909 and 0.7885 R^2 values, respectively. The correlation between the specific gravity and the edge crushing stiffness was low ($R^2=0.469$). However, the obtained correlations for the investigated alternative fasteners were still better than the correlations observed for nails.
- Including the size of the fasteners into the correlation model for the head embedment improves the model's predictive ability indicating that it is an important factor to consider. In historical studies, the head diameter of the nails was not investigated as a separate variable thus it was not included into the models.

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11 Future Research

Based on the findings and limitations of this study, the following recommendations for further research may be made:

- More replicates for each test type to provide a higher confidence level in the data
- Investigation into the differences in head embedment stiffness of lag screws and carriage bolts
- A study investigating how the bearing area of a fastener or washer affects the stiffnesses and include this in a developed model
- A study investigating how differing specific gravities in the blocks and deckboards affect edge crushing stiffness
- Development of a finite element analysis model for the pallet joint using the stiffnesses from this study to predict the rotation modulus
- Run another study with nails to compare the results from that study with the results from the current study

The data collected in this study was done by providing 10 samples per fastener and wood combination. This was done to give a confidence level of over 75%. However, to be more confident in the data, more replicates could be run to determine if the prediction models that were developed through this investigation were accurate or if the estimations of stiffness for both the head embedment stiffness and shank withdrawal stiffnesses need to be amended. The head embedment stiffnesses investigated for the two fastener types, lag screws and carriage bolts, were similar enough to not be seen significantly different during analysis. This was not expected since the contact areas for lag screws and carriage bolts are different. An investigation into this phenomenon could lead to more insight into why the pallet joints behave this way and a better understanding of predicting the total stiffness associated with pallet joints as a whole. A study on different sized washers and fastener heads could investigate how the head embedment and moment rotation stiffnesses are affected by the bearing areas, and this data could lead to an improved model and a better understanding about how the fastener heads interact with the top of a pallet joint. Adding bearing area into the model could also provide a more accurate predicted stiffness for the pallet joints. A finite model could be developed to predict the rotation modulus

of the pallet joints by using the stiffnesses that were produced in this study as variables to predict the complete behavior of a pallet joint. The original study was done in 1987; the model used in that study is no longer accessible, and technology has advanced to a much higher level than it was in that time period. Creating a new model with updated software could make it easier to reliably predict the rotational modulus of a complete pallet joint. Running a new study with nails so that the data from that study can be directly compared with the data from this study could prove beneficial.

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Appendix

Table 1A: Effect Test from Head Embedment Stiffness ANOVA Test

▼ Effect Tests						
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Column 5	2	2	1.3787e+10	143.2273	<.0001*	
Column 6	2	2	4598702986	47.7739	<.0001*	
Column 5*Column 6	4	4	341158095	1.7721	0.1369	
Column 7	1	1	135836.359	0.0028	0.9577	
Column 5*Column 7	2	2	87296300.2	0.9069	0.4058	
Column 6*Column 7	2	2	11722162.7	0.1218	0.8854	
Column 5*Column 6*Column 7	4	4	29072207.6	0.1510	0.9623	

Table 2A: Effect Test from Shank Withdrawal Stiffness ANOVA Test

▼ Effect Tests						
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Wood	2	2	1.5959e+10	146.9840	<.0001*	
Size	2	2	4741578368	43.6706	<.0001*	
Wood*Size	4	4	398236038	1.8339	0.1248	
Type	1	1	213163838	3.9265	0.0492*	
Wood*Type	2	2	314306970	2.8948	0.0582	
Size*Type	2	2	3865589.02	0.0356	0.9650	
Wood*Size*Type	4	4	42500057.5	0.1957	0.9403	

Table 3A: Effect Test from Edge Crushing Stiffness ANOVA Test

▼ Effect Tests						
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Wood	2	2	3109394400	190.2391	<.0001*	
Fastener Size	2	2	1650384632	100.9739	<.0001*	
Wood*Fastener Size	4	4	17531327.5	0.5363	0.7093	
Fastener Type	1	1	36173439.1	4.4263	0.0369*	
Wood*Fastener Type	2	2	51921.3726	0.0032	0.9968	
Fastener Size*Fastener Type	2	2	2059799.52	0.1260	0.8817	
Wood*Fastener Size*Fastener Type	4	4	9266513.28	0.2835	0.8884	