LATERAL MOVEMENT OF UNBRACED WOOD COMPOSITE I-JOISTS EXPOSED TO DYNAMIC WALKING LOADS

by

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Abstract

The research summarized in this thesis is comprised of an experimental analysis of the mechanical behavior of a wood composite I-joist with different bracing configurations exposed dynamic walking loads. Three 16 in. deep GPI® 65 I-joists were simply supported and laid parallel to each other, while the bracing was attached to the top flange. Five different brace stiffnesses were used: zero stiffness (control), 1.2 lb/in., 8.5 lb/in., 14.0 lb/in. and infinitely stiff. Two different brace configurations were used: one-quarter of the span length (60 in.) and one third the span length (80 in.). The dynamic walking loads consisted of human test subjects attached to a safety platform walking across the I-joist at a designated pace.

Experimental results for this research consisted of the I-joist's lateral accelerations, lateral displacements and twist. An Analysis of Covariance (ANCOVA) was used for the statistical analysis of the results and was performed for each measurement. The statistical analysis determined the effects of different bracing configurations, stiffnesses, measurement locations as well as test subjects' weight and occupation.

Test results and observed trends are provided for all test configurations. Lateral displacement and twist experienced the same trend throughout the experiment: as brace stiffness increased, lateral displacement and twist decreased. This correlated with basic beam theory and

bracing fundamentals. It should be noted that as the stiffness increased, the effect on lateral displacement and twist response decreased.

However, the trend for lateral displacement and twist was not observed for the lateral accelerations. The 1.2 lb/in. brace stiffness had much larger lateral accelerations for the 60 in. brace configuration throughout the span and were also larger at the bracing point for the 80 in. brace configuration. This could have been due to the energy applied from the springs or a natural frequency of the I-joist system could have been reached during testing. However, the other four brace stiffnesses followed the same trend as the lateral displacements and twist.

In addition, this research demonstrates a method for the measurement of lateral buckling due to worker loads. The mitigation of lateral buckling can use appropriate bracing systems. The measurements of the change in lateral buckling behavior can be used to develop safety devices and ultimately ensure the protection of construction workers.

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Chapter 1: Introduction

1.1 Background

Construction sites can be hazardous places for people to work. Building construction requires the movement of people, equipment and materials through uncompleted structures, which may not be able to carry these loads at certain construction phases. For instance, wood framed wall members do not develop lateral resistance until the sheathing or other wall covering is installed. This lack of strength and resistance creates a hazardous working environment. A particularly hazardous element involves elevated areas where workers are more susceptible to falls.

According to the Bureau of Labor Statistics (BLS), the National Census of Fatal Occupational Injuries (CFOI) in 2005 showed that 767 falls were recorded which constituted 13% of all the fatal occupational injures in the United States. Of these 767 recorded incidences, 662 were falls to a lower level (BLS 2005). In 2006, the number of incidents increased to 809 recorded falls, which constituted 14% of all the fatal occupational injuries in the United States. Of these 809 recorded incidences, 728 were falls to a lower level (BLS 2006). Fatal falls occurred on average about twice a day in the U.S. during 2006. Based on a study by Huang and Hinze (2003), the average proportion of falls before 1996 was 34.1%; however, the proportion of falls has increased to 38.4% in the following years. Not only did the occurrence of falls increase, but falls also accounted for 33% of injuries and fatalities in the U.S. construction industry between the years of 1985 to 1989 (Huang and Hinze 2003).

According to Suruda et al. (1995), falls are the fourth leading cause of death in the workplace in the United States with over 500 falls per year and falls account for one-half of the fatal accidents at work in England. In Denmark from 1993 to 1999, 23% of all construction related fatalities were falls from a higher level (Bobick 2004). In addition, construction-related falls are prevalent worldwide and not only in the United States.

Falls are not only devastating to the individual and their family, but can also be costly to the company. When a worker is either killed or injured, work on the job can slow down or stop completely. According to Hinze and Lytle (1991), injury rates for construction workers are almost double and death rates are almost triple that of other industries. There is speculation that higher injury rates cause more disruption of work. Lipscomb et al. (2003) found that in a ten year period, work time lost on the job due to injuries or fatalities cost companies nearly $17,061,436. This cost is equivalent to about 199,218 paid days for out-of-work time, which is about 98 person years of full-time work. However, work coming to a halt is not the only cost that supervisors might incur. Paying for a worker to go to the hospital or workers' compensation can become expensive. Medical costs and impairment costs totaled $30,709,190 during the same ten year period (Lipscomb et al. 2003).

However, all falls do not occur in the same manner or on the same kind of construction job site. One construction site which has received little attention is the residential construction site. A possible cause of falls may be due to workers walking across wood composite I-joists before sheathing is installed on top of them. When this happens the I-joist experiences lateral-torsional buckling (LTB), or, simply lateral buckling, causing the beams to deflect out-of-plane and rotate about the longitudinal axis (Timoshenko and Gere 1961). Only beams with a depth greater than their width can experience lateral buckling. Lateral buckling occurs due to out-of-plane movement, instability or eccentric loads (Zirakian and Showkati 2007). This instability is due to lack of out-of-plane stiffness and occurs only if the compression flange is unbraced. For a simply supported beam the top flange is the compression flange.

A common way to prevent lateral buckling from occurring is to provide lateral bracing on the compression edge (Zahn 1985), such as sheathing or blocking. Since the phase of construction examined here is before any permanent bracing is installed, temporary bracing was the primary focus. To date, there is little to no research on the use and placement of bracing for wood composite I-joists.

1.2 Objectives

The main goal of this research was to analyze the mechanical behavior of different bracing configurations to prevent lateral buckling of wood composite I-joists due to the weight of construction workers walking across the I-joist. Temporary bracing was used to examine the relationship between lateral acceleration, lateral displacement and twist to brace stiffness and configuration (spacing). This temporary bracing was placed on the top flange (compression flange) for maximum efficiency and attached to adjacent I-joists of equal lateral stiffness. The specific objectives were:

1) Analyze the relationships of lateral acceleration, lateral displacement and twist with respect to the brace configuration.
2) Analyze the relationships of lateral acceleration, lateral displacement and twist with respect to the brace stiffness.

1.3 Significance

The experimental testing conducted throughout this research project yielded a better of temporary bracing for wood composite I-joists. The first objective analyzed the I-joist behavior with two different brace configurations and showed the different behavior's response as the quantity of the bracing varied. The second objective analyzed the I-joist behavior to five different brace stiffnesses and showed how the I-joist's behavior varied as the stiffness was increased.

This expanded knowledge of temporary bracing will yield a better understanding of bracing fundamentals and could lead to better designs of temporary bracing. Consequently, this should lower the number of fatalities and injuries due to falls.

Chapter 2: Literature Review

2.1 Introduction

This chapter summarizes previous research studying lateral stability and excitations, and includes methods to improve them through means of bracing. Because there is little research available on wood materials, a majority of the research described in this area is for steel beams, but the same concepts still apply to wood composite I-joists.

2.2 Lateral Buckling and Stability

Lateral stability pertains to a beam's resistance to lateral, or out-of-plane, deflection as well as torsion. It is critical during construction because the structure is incomplete and lacks key support. During lateral stability calculations for a simply supported beam, it is assumed the beam is allowed to bend and experience axial deflections at the supports but no torsional rotation may occur at the supports (Zahn 1985). However, this may not always be the case throughout the life of the structure.

Lateral buckling, also called lateral-torsional buckling (LTB), is a phenomenon experienced by beams with a depth greater than the width and occurs when a flexural load is applied to the unbraced beam. The plane in which the load is applied must have longitudinal flexural rigidity greater than the transverse flexural rigidity. The beam is considered stable until a critical load is reached which will cause the beam to buckle or bend about the weak axis, out-of-plane bending, and rotate about its longitudinal axis (Zirakian and Showkati 2007). As the applied load exceeds the critical load, the compression part of the beam begins to rotate about its longitudinal axis (Timoshenko and Gere 1961).

When a beam laterally buckles, it buckles in one of two ways: elastic or in elastic. Elastic buckling occurs when the beam buckles but returns to its non-deformed shape once the load is removed. Thus, the beam did not exceed its critical load which is calculated by the equation from Timoshenko and Gere (1961) for a generic homogeneous member:

$$P_{cr} = \gamma_2 \frac{\sqrt{EI_x C}}{l^2} \tag{1}$$

where,

P_{cr} = critical load

γ_2 = dimensionless factor

E = modulus of elasticity

I_x = area moment of inertia about the x-axis

C = torsional rigidity

l = span length

In elastic buckling occurs when the beam loading surpasses the beam's yield strength and it is unable to return to its non-deformed shape. This is not a focus of this research because the loads applied to the I-joist are not great enough to cause in elastic buckling. Previous research from Hindman et al. (2005a) did not observe in elastic buckling of I-joists, while Burow et al. (2006) did experience in elastic buckling of short span I-joists.

There are a number of factors that control the critical load. Flint (1952) examined a theory involving the placement of the load on the beam as the controlling factor for lateral stability of steel beams. Flint (1952) found that if the load was placed above the shear center the value of the critical load decreased. However, if the load was placed below the shear center, the critical load increased. This result was due to the additional couple about the shear center that was created due to bending stresses in the beam. When a beam is in positive bending, the top of the beam is in compression while the bottom of the beam is in tension. These two opposite forces creates the couple.

2.3 Lateral Buckling of Wood Members

For a wood member that is simply supported and used in a bending application, the flexural gravity load induces stresses and strains parallel to grain (Hooley and Madison 1964) and causes the top of the beam to be in compression while the bottom is in tension. According to current wood design methods (NDS), lateral buckling is calculated by considering the compression flange to be a column restrained in the axis of the web (AF&PA 2005b). Therefore, the length of the member is critical to its lateral stability. Hooley and Madsen (1964) examined the depth-breadth ratio, also called depth-width ratio, as well as the length of the member to determine the relationship with the critical load of rectangular glued laminated beams. The depth-breadth ratio was not related to the resistance of lateral buckling as many building codes assume. However, a slenderness ratio was found consisting of $L_e d/b^2$ where L_e was the effective beam length, d was the depth and b was the breadth. Hooley and Madsen (1964) found that this slenderness ratio to relate to buckling behavior and with the concept of long, intermediate, and short beams should lead to safer and more economical design practices.

However, material section properties are not the only factors that play a role in lateral stability. Another factor is the different materials, or combination of different materials used in the beam. Hindman et al. (2005a) examined lateral buckling of composite I-joists using different flange materials, laminated veneer lumber (LVL) and laminated strand lumber (LSL), with the same web material, oriented standboard (OSB). The current design equations were found to be overly conservative and did not account for torsional stiffness or warping. Hindman et al.

(2005b) investigated the torsional stiffness of composite I-joists with different flange materials but with the same web material. No significant difference was found in torsional stiffness with the different flange materials and widths.

2.4 Bracing of Beams to Prevent Lateral Buckling

There are a number of ways to prevent lateral buckling from occurring. One way is by increasing the size of the compression flange to increase the longitudinal and torsional stiffness simultaneously (Zhu et al. 2005). The most common way to prevent lateral buckling is with lateral bracing. Lateral bracing requires a combination of flexural and torsional restraint (Yura 2001).

Bracing for beams can be divided into two main categories, lateral and torsional. Lateral bracing provides resistance to lateral displacement, and the effectiveness of it is measured by the amount of twist of the cross section it can restrain. Torsional bracing provides resistance to twist directly. The best form of bracing provides a combination of lateral and torsional bracing that is attached to the compression flange. For a simply supported beam, bracing the top flange is the most effective because this portion of the beam is in compression during positive bending. Bracing the bottom flange is almost completely ineffective. An example of this would be a concrete deck poured on top of a steel beam. The concrete is installed on the compression flange and is stiff enough to provide lateral restraint as well as torsional restraint (Yura 2001). Another example would be to install OSB on top of an I-joist floor system. This would also provide enough stiffness for lateral and torsional bracing of the compression flange (Zahn 1985).

An additional way to improve bracing is through web stiffeners. Lateral bracing as well as torsional bracing increases its effectiveness if web stiffeners are used at the bracing points. Additional support of the web is due to the amount of load that is transferred through the bracing, causing the web to distort. A web stiffener stiffens the web and prevents web distortion (Yura 2001).

Bracing systems are divided into four main groups: relative, discrete, continuous and lean-on (Yura 1995). These bracing systems provide different approaches to improving stability, and when an engineer designs lateral bracing, there are two criteria that must be met for each system: strength and stiffness (Zahn 1984).

2.4.1 Bracing Systems

This section describes the different bracing systems. Unless cited otherwise, the material is from Yura (1995). There are a number of ways engineers can decide to brace their structures. All bracing methods can be divided into four main categories: relative, discrete, continuous and lean-on. Relative and discrete bracing are the most common bracing systems and can be used in combination with each other.

Relative bracing is when a node or story is braced to another node or story in which the two points move relative to one another. Examples of relative bracing are X-bracing and K-bracing, also called Chevron bracing. This type of bracing is easy to install but very uneconomical. Relative bracing can use counters or regular members. When counters are used, the bracing can only function in tension, such as a steel cable. If regular bracing is used, the braces can also experience compression, and column buckling should be considered for longer lengths of bracing. If needed, the point where two braces intersect can be considered to be braced by discrete bracing, thereby lowering the unbraced length of the braces.

Discrete bracing, also called nodal bracing, is when a single point is braced and its movement is governed by the brace. One example of discrete bracing, as discussed earlier, would be the intersection of two members used for relative bracing. Assuming that each member meets the stiffness requirements, the unbraced length of a column can be shortened. The main use for discrete bracing is to decrease the unbraced length of the column which will increase the load that causes the column to buckle.

The third bracing system is continuous bracing. Continuous bracing is when bracing is attached along the entire length of a member. This occurs during the later construction phase of light frame wood structures when the diaphragm is attached and provides continuous bracing of the top flanges causing lateral buckling to no longer be a concern. According to the NDS (2005), if the entire length of a member is laterally supported on the compression flange and the points of bearing prevent rotation and have lateral support, then the member is considered to have continuous lateral bracing. This bracing is commonly used in floor systems composed of wood composite I-joists covered by oriented strand board (OSB). The composite action of the two materials is provided by a combination of adhesive and mechanical fasteners.

The fourth type of bracing system is lean-on bracing. Lean-on bracing is when a member relies on another adjacent structural member for its bracing. The original member's resistance to lateral buckling now depends on the lateral movement of the supporting member. As expected, this system is more effective when the supporting member is laterally tied down (Yura 2001). The two buckling modes for this bracing are sway and no sway. If the adjacent member that is providing stiffness for the bracing is not stiff or rigid enough, the supporting member will not provide adequate support and the original member will buckle in sway mode. When the supporting member is adequately stiff, inflection points form at the bracing points and the original member's unbraced length is decreased. If the adjacent member does not have the adequate stiffness required for bracing, then the lean-on bracing is very ineffective.

2.4.2 Stiffness and Strength of Bracing

Once the type of bracing is decided, an engineer must design the bracing for both strength and stiffness. Each bracing system has its own specific design requirements, but in general, the two main variables are the unbraced length of the member and the amount of load the bracing system is supporting (Yura 1995). An engineer must take these requirements into consideration as well as material behavior under certain loadings. In designing a bracing system, three initial steps that must be taken include choosing allowable deflections, calculating the required stiffness, and checking the strength of the brace (Zahn 1984). Allowable deflection is a serviceability issue that must be met in order to size the required member to withstand the deflection from the structural loads. Not only does the size of the member dictate the amount of deflection, but also the brace spacing.

Once the amount of bracing is chosen, the bracing stiffness required must be found. The purpose of a brace is to prevent lateral movement and strengthen the member. Theoretically, if a brace is infinitely stiff, the member will not experience lateral deflection at the bracing point and an inflection point will form at the point of bracing. However, if the bracing stiffness is not great enough, then the member will deform in the same shape as if it were not braced (Mutton and Trahair 1973).

Bracing stiffness was observed in an experiment by Zhu et al. (2005) where, depending on the number of lateral restraints, the top flange of a wood based composite I-joist formed one or more sine waves with inflection points at the lateral restraints. Once bracing stiffness increased and the deformed shape changed, additional stiffness becomes less effective (Yura 1995). This is where a design engineer must exercise professional judgment to find the optimal stiffness with economical brace spacing.

Once the stiffness has been found to be sufficient according to the material specifications, the strength of the brace must be checked. The strength of the brace must be sufficient enough to withstand the tensile and/or compression forces experienced due to lateral deflection (Mutton and Trahair 1973). This ensures that the structure can experience lateral deflections without the bracing becoming overstressed and experiencing failure.

2.4.3 Temporary Bracing of Wood Composite I-Joists

Since the advent of wood based composite I-joists, engineers have raised numerous concerns about the lateral stability of the I-joists. One way to improve the lateral stability is to attach a floor or sheathing to the compression flange. If the floor or sheathing is stiff enough, then the I-joist is considered to be fully laterally braced. The equations in the Manual for Engineered Wood Construction (AF&PA 2005a) and NDS (AF&PA 2005b) are for bracing when the floor or sheathing is attached. Research on temporary bracing for wood based composite I-joists could not be found. However, there are technical design papers from I-joist manufacturers that recommend ways to temporarily brace them during construction.

One paper from iLevel (2008) recommends using 2x4 or 1x4 dimension lumber attached to the bottom flange flat wise with two 2½ in. long screws to provide temporary bracing. Figure 1a shows the proper way to install the temporary bracing. If the floor movement is still too great, iLevel also suggested attaching an edgewise additional 2x4 or greater to the already attached 2x4. This additional 2x4 or greater should be attached with a 2½ in. 8d box nail every 12 in. on-center. Figure 1b shows how the additional 2x4 or greater should be installed (iLevel 2008).

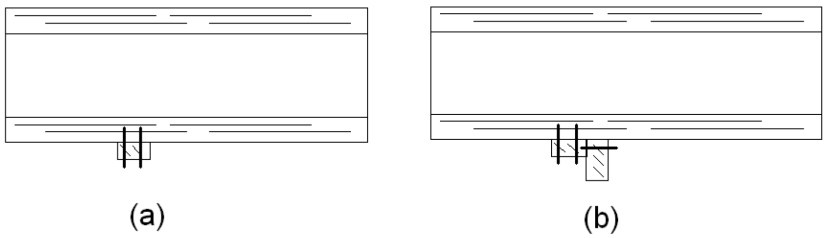

Figure 1: Temporary Bracing

iLevel recommends that these methods of temporary bracing should be used no more than 8 ft on-center (iLevel 2008). However, providing lateral support on the tension face is not an effective bracing method. These recommendations do not have any published supporting research, but do give ideas for construction workers to increase the safety of their tasks.

2.5 Lateral Excitation

The previous section dealt with past research on vertical or strong axis, movement of floor systems and not lateral, or weak axis, movement. Lateral excitation is when a structure oscillates in the lateral direction, or weak axis, and is an important factor to consider for footbridges or structures that are not completely laterally restrained. Also, people walking in unison is a major factor causing lateral excitation to increase (Nakamura and Kawasaki 2006). There is very little research done on this topic and, based on previous occurrences, dominantly occurs in pedestrian bridges.

One recent example of lateral excitation problems is the Millennium Bridge built in London. Lateral excitation was caused by synchronous pedestrian walking across the span at a frequency similar to the bridge's natural frequency. This increased the bridge's lateral acceleration and caused pedestrians to become doubtful of the bridge's structural integrity. The bridge was closed for 20 months, and then reopened to the public with proper damping devices installed on the bridge (Nakamura 2004). Groups of people walking in unison are not a concern for this project but it does show that people may change their walking patterns to fit the movement of a structure and, ultimately, increase the movement of a structure.

2.6 Summary

Currently, research on wood based composite I-joist is limited. A majority of past research does not include unbrace I-joists. In addition, lateral vibration research and knowledge is very limited. The goal of this research is to examine an I-joist's mechanical behavior under dynamic loads and different bracing configurations. Mechanical behaviors studied include lateral accelerations, lateral displacements and twists. This research will contribute to current research and knowledge of wood composite I-joists.

Chapter 3: Materials and Methods

3.1 Introduction

This chapter describes the materials and methods incorporated in this research project to analyze the relationship between lateral peak acceleration and brace spacing as well as the relationship between lateral peak acceleration and brace stiffness. It will also explain the reasoning of the decisions made for experimental testing so that credible results would be obtained.

3.2 Materials

The materials used for this experiment consist of a safety platform, a series of GPI 65 wood composite I-joist, compression springs and bracing devices that was fabricated from steel plates. All of these materials were tested at the Brooks Forest Products Center at Virginia Tech.

3.2.1 Safety Platform

The safety platform constructed for this experiment is twenty feet long by approximately five feet wide, and can be seen in Figure 2. It consists of hand rails made from 2x4 LVL beams that are within arms reach of the test subjects, if they feel the need to use them. The hand rails are attached to frame at each end of the safety platform, which has been stiffened with additional LVL beams to ensure as little movement as possible. The frame consists of 4x4 LVL columns that attached at the base with 2x6 LVL beams and attached at the top with an LVL header. Attached to the top of the header with two bolts at each end is a W8x13 A992 steel I-beam. This I-beam supports a trolley that rides along the bottom flange and is more than adequate to support the weight of a test subject.

Figure 2: Safety Platform

3.2.2 GPI 65® Wood Composite I-Joists

The wood based composite I-joist that was used for this experiment was a 16 in. deep GPI® 65 I-joist from Georgia Pacific. The flanges of the I-joist were 2 $^{7}/_{16}$ in. wide and made from laminated veneer lumber (LVL) while the web was constructed from was oriented strand board (OSB). The 16 in. depth and narrow flanges ensured less lateral stability and maximized lateral movement. The stiffness of the I-joist, or EI, was 877,000,000 lb-in.^{2} (ICC Evaluation Services, Inc. 2005). Figure 3 displays the cross-sectional dimensions of a 16 in. deep GPI® 65 I-joist.

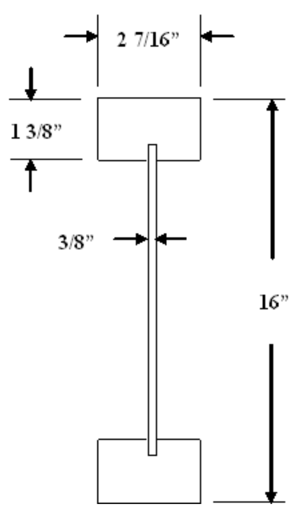

Figure 3: 16 in. Deep GPI® 65 Cross-Sectional Dimensions

Three of these I-joists were placed longitudinally parallel inside of the safety platform and supported by built-up end supports. A span of 20 ft was used and attached at the ends with IUT316 Simpson Strong-Tie face mount hangers to simulate a simply supported connection. The hangers were supported by and connected to an LVL end support which simulated a rim board as a rigid member. This connection was used to model the attachment of I-joists on a construction site. Since bracing stiffness and spacing are the variables in this experiment, only the middle I-joist's mechanical behavior was recorded and analyzed. Figure 4 displays the layout of the I-joists, as well as the end supports.

(a) I-Joist Layout (b) End Supports

Figure 4: I-Joist Layout and End Supports

3.2.3 Compression Springs

Three different compression springs with varying stiffnesses were used in this experiment. The stiffnesses consisted of 1.2 lb/in., 8.5 lb/in. and 14.0 lb/in. The springs were covered by rigid tubing during testing to prevent buckling of the springs. These compression springs were attached by a bracing device that was fabricated from steel plates. Figure 5 shows the compression springs used for this experiment.

Figure 5: Compression Springs

3.2.4 Bracing Device

The bracing device connected the compression springs to the I-joist and was fabricated from steel plates. The steel plates were cut to size and welded together so that they fit on the top flanges of the I-joists. A ¼ in. gap between the sides of the device and the sides of the I-joist's top flange was provided and a ½ in. diameter bolt was used to tighten the bracing against the top flange. The springs were attached to the bolts through pinning or welding, depending on the spring size. This ensured that movement of the bracing device would not occur which could have hinder the springs' contribution to the I-joist's movement. Figure 6 shows the bracing devices used for the middle I-joist as well as the two outer I-joists. The bracing device for the middle I-joist had springs attached to each side of the top flange, whereas the bracing devices for the outer I-joists only had one bolt and one spring attached to the top flanges.

Figure 6: Bracing Devices

3.3 Method

This experiment measured the mechanical behavior of an I-joist induced from dynamic loads with different brace stiffnesses and configurations. The dynamic loads consisted of human test subjects walking across the I-joist to a beat produced by an electronic metronome. The I-joist's movement was measured with a combination of accelerometers and string potentiometers installed at designated locations along the span.

3.3.1 Brace Stiffnesses and Configurations

For this experiment, five different brace stiffnesses were used: a control of no bracing, a solid bar representing, a very large bracing stiffness and three intermediate stiffnesses created by compression springs. Compression springs of stiffness 1.2 lb/in., 8.5 lb/in. and 14.0 lb/in. were obtained from Grainger. The spring stiffnesses were verified by stretching and compressing the springs using the MTS Universal Testing Machine. The infinitely stiff spring consisted of a ½ in. diameter threaded steel rod with a stiffness of approximately 400,000 lb/in. (considered to be infinite when compared to other stiffnesses used) and showed how the I-joist mechanically behaved when the bracing was very stiff or rigid. The zero stiffness consisted of no bracing.

The springs were attached to bracing devices that were spaced along the I-joist at two different configurations (spacings), one-quarter and one-third of the span length, 60 in. and 80 in. respectively. These brace configurations were chosen for simplicity and allowed for an understanding as to the amount of bracing needed to decrease the movement of an I-joist by a significant amount.

3.3.2 Accelerometers and String Potentiometers

Accelerometers and string potentiometers were used to measure the mechanical behavior of the I-joist. Figure 7a displays the accelerometers used. The largest and the smallest accelerometer are one axis accelerometers while the middle one is a tri-axial accelerometer. A one axis accelerometer measures acceleration in one direction, whereas tri-axial accelerometers can measure acceleration in three different directions. Only one signal output was used from the tri-axial accelerometer. All three accelerometers were from PCB Piezotronics, Inc. and were digitally analyzed in RT Pro (5.5, LDS/SPX, Fremont, CA). In addition, Figure 7b displays a picture of a string potentiometer used for the experiment. The string potentiometers were string fed, spring loaded, and had a range of up to 8 in. with a sensitivity less than 1% and allowed for readings of up to 4 in. in each direction.

(a) Accelerometers **(b) String Poteniometer**

Figure 7: Accelerometers and String Potentiometers

Figure 8 displays the layout for each point of interest for the accelerometers and string potentiometers. The accelerometers and string potentiometers were installed at each point of interest. The accelerometers were attached to a metal strip that was screwed into the top of the I-joist web of the I-joist. The string potentiometers that measured the bottom flange movement were attached to an eye bolt that screwed into the bottom on the bottom flange. The string potentiometers that measured the top flange movement were hooked to an eye bolt attached to an angle that protruded out from the side of the top flange. This prevented test subjects from stepping on the eye bolt and causing damage to the string potentiometers. The accelerometers and string potentiometers measured accelerations and displacements, respectively, in the lateral direction of the I-joist. The lateral displacement was measured by using the string potentiometer attached to the top flange. Since the string potentiometers recorded the lateral movement at two locations for each point of interest, and using the assumption that the I-joist's depth remained constant, the twist of the I-joist was calculated as well.

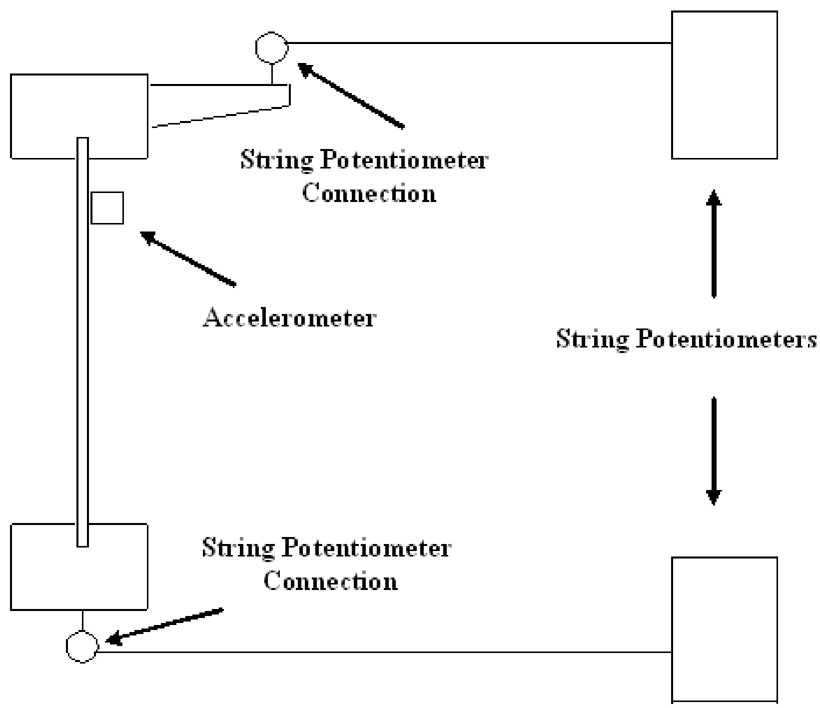

Figure 8: Accelerometer and String Potentiometer Connection to the I-Joist

Continuous readings were taken as each subject walked across the I-joist and stopped once each test subject reached the opposite end of the I-joist. Sensors were only installed on half the I-joist since the behavior was assumed to be symmetrical about mid-span. Once the data from the accelerometers and string potentiometers were measured, the largest lateral acceleration, lateral displacement and twist at each point of interest for each brace stiffness and configuration were retrieved. This was done for each test subject and yielded a total of 350 data points for each mechanical behavior: 200 for the 60 in. bracing configuration and 150 for the 80 in. bracing configuration.

3.3.3 Testing Method

For this experiment, human test subjects walked across a wood composite I-joist. Different bracing stiffnesses and configurations were used, with a control of no bracing for comparisons. Accelerometers and string potentiometers were installed on the I-joist at different points of interest to record the I-joist's mechanical behavior. Results from testing measured the I-joist's lateral acceleration, lateral displacement and twist to determine the role of bracing in mitigating lateral movement.

The test subjects were equipped with a tool belt with up to 9.6 lbs of common tools to simulate additional weight and eccentricities while walking across the I-joists. The test subjects consisted of 14 students and 6 construction workers. Students were male Virginia Tech graduate students between the ages of 22 and 25, with one student being 30. Construction workers were recruited from two different contractors. All were male with ages ranging from 23 to 36. The population of test subjects included those familiar with walking on I-joists as well as those unfamiliar with walking on I-joists. Each test subject was given a unique identification number for each test (1-10 for the 60 in. brace configuration and 21-30 for the 80 in. brace configuration). All subjects were secured by a safety harness attached to the safety platform while walking across all testing. The test subjects were asked not use the hand rails as support unless they lost their balance to prevent the dispersal of body weight to the hand rail, thereby reducing the load applied to the I-joist. The tests subjects were asked to walk to an electronic metronome at a beat of 45 steps per minute so that a constant walking speed would be used throughout testing. All testing conformed to standards of the Virginia Tech Institutional Review Board (IRB) for using human subjects. Figure 9 shows a picture of a test subject walking across the I-joist while attached to the safety platform.

Figure 9: Test Subject Walking Across the I-Joist

The different test setups consisted of changing the stiffness as well as the configuration (spacing). To simulate bracing, the bracing devices described earlier were attached to the top flange every 60 in. and then every 80 in. All five stiffnesses (0 lb/in., 1.2 lb/in., 8.5 lb/in., 14.0 lb/in. and ∞ lb/in.) were tested with the two different configurations. Figure 11 displays the layout of sensors and bracing on the I-joist. “Bracing Points” denotes where bracing was attached and “Points of Interest” denotes where accelerometers and string potentiometers were located. In addition, Table 1 shows the different combinations tested and the number of tests performed for each combination. Test setups A and F are the control samples.

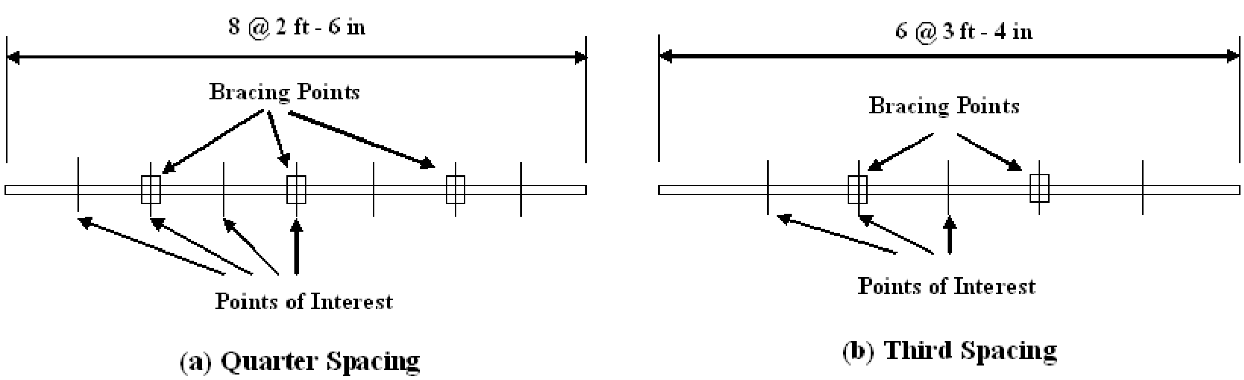

Figure 10: Placement of Sensors on I-joist

Table 1: Testing Layout

Test	Spring Stiffness (lb/in.)	Bracing Device Configuration	Number of Test Specimens
One-Quarter Span Length Spacing (60 in.)			
Test Setup A	0.0	5 ft - 0 in	10
Test Setup B	1.2	5 ft - 0 in	10
Test Setup C	8.5	5 ft - 0 in	10
Test Setup D	14.0	5 ft - 0 in	10
Test Setup E	∞	5 ft - 0 in	10
One-Third Span Length Spacing (80 in.)			
Test Setup F	0.0	6 ft - 8 in	10
Test Setup G	1.2	6 ft - 8 in	10
Test Setup H	8.5	6 ft - 8 in	10
Test Setup I	14.0	6 ft - 8 in	10
Test Setup J	∞	6 ft - 8 in	10

Once the test subjects walked across each test setup, they were asked to fill out a survey that inquired as to the difficulty of walking on the I-joist. Questions included whether walking was made more difficult closer to the bracing points or in the middle of the bracing points, as well as open-ended questions about their opinions. After each participant had walked all five test setups for each spacing, they were asked on a scale of 1-5 how much the bracing improved the ease of walking on the I-joist. They were also asked at what bracing they began to feel comfortable, if the walking speed designated was too fast and asked to provide any additional comments. In addition, the subjects were asked to record their weight, height, age, ethnicity and occupation on the survey as well.

Readings from all the accelerometers and potentiometers were recorded in a continuous reading as a test subject walked across the I-joist. Since the accelerometer and string potentiometer DAQ were linked to separate computers, the data could not be acquired simultaneously. In order to correlate the data, hand notes were taken as each subject walked across the I-joist. These hand notes consisted of notes taken during the testing when something of significance was observed. Notes were primarily taken when spikes in the acceleration were observed or as the I-joist began to sway at a large magnitude. Once the test subject reached the opposite end of the I-joist, the test was stopped and the next subject was asked to walk across the I-joist.

Once all the data were extracted, separate Analyses of Covariance (ANCOVA) for each mechanical behavior were performed using JMP® (7.0.1, SAS, Cary, NC) to assess the effects of brace stiffness (five levels), brace location (seven levels, i.e. four locations for the 60 in. brace configuration, three locations for 80 in. brace configuration) and participant reaction on the I-joist's kinematics (lateral acceleration, lateral displacement and twist). A mixed-factor fixed-effects model was used, with brace stiffness and configuration as within-subject factors and occupation as a between-subjects factor. Body weight was also included as a continuous covariate. Table 2 shows the model that was input into JMP®. The "[ ]" denotes that factor is nested while "x" denotes that the factors are crossed.

Table 2: Statistical Model Summary

Independent Variables	Dependent Variables
Occupation	Lateral Accelerations
Subject $_{\text{Random Effect}}$ [Occupation]	Lateral Displacements
Weight	Twist
Location	
Stiffness	
Location x Stiffness	

To achieve normality, each of the dependent measures was log transformed prior to analysis; however, summary of the statistics are provided in the untransformed values. Also, a visual inspection check was performed for outlying measures, which revealed a single outlying measure was evident and removed prior to analysis. The outlying measure was found for subject 30 at the mid-span location for the 80 in. brace configuration. Additional analyses confirmed that including this outlier did not change the major results reported. Post-hoc pairwise comparisons were done using the Tukey's HSD and several contrasts were used to assess the effects of brace configuration. Results from all statistical analyses were considered significant when $p < 0.05$.

Chapter 4: Results and Discussion

4.1 Summary

This chapter contains the results obtained from methods discussed in Chapter 3. All the data obtained from the experiment was analyzed using the statistical software discussed in Chapter 3 and the results have been organized in tables and graphs to help analyze the results. This section will start with the comparison of the different brace configurations (spacings), then compare the mechanical behaviors at different points of interest, then compare the behaviors for each stiffness to the zero stiffness (control sample), and end with the comparison of the behaviors to the subjects' weight and occupation separately. This will correlate the different variables and data that were gathered during testing.

4.2 Brace Configuration Comparisons

This section compared the different brace configurations to understand if the amount of bracing had a significant effect on the I-joist's mechanical behavior. For the comparison of the brace configurations, each dependent variable (lateral acceleration, lateral displacement and twist) was analyzed separately to see any significant differences. Once numerical analysis was completed, a statistical analysis was performed to verify any results and conclusions.

4.2.1 Lateral Accelerations

The lateral acceleration data consisted of 350 data points: 200 data points for the 60 in. brace configuration and 150 data points for the 80 in. brace configuration. Table 6 displays the averages of the lateral accelerations for each brace stiffness at each brace configuration and the percent differences between each brace configuration. The 1.2 lb/in. had the largest percent difference between the two brace configurations, whereas the infinitely stiff bracing had the smallest percent difference. Another important observation is the percent difference of the zero stiffness bracing. In theory, these values should be identical since they represent the I-joist acting without any bracing. This shows there are differences in acceleration between the two groups of test subjects that walked across the I-joist. The increased amount of string potentiometers used for the 60 in. brace configuration could have had an affect on the I-joist behavior since the string potentiometers were spring loaded. This increased amount of lateral stiffness could have decreased the lateral accelerations. However, the stiffness of the string potentiometer is not known. In addition, since the string potentiometers remained the same throughout the experiment, the comparisons are still consistent and do not discredit any conclusions.

Table 3: Evaluation of Lateral Accelerations for Both Brace Configurations at Each Brace Stiffness

60 in. Brace Configuration		80 in. Brace Configuration		% Difference[1]
Stiffness (lb/in)	Average (ft/s^2)	Stiffness (lb/in)	Average (ft/s^2)	
0.0	18.366	0.0	22.858	19.65%
1.2	38.045	1.2	22.477	-69.25%
8.5	15.833	8.5	15.092	-4.90%
14.0	13.645	14.0	14.826	7.95%
∞	11.549	∞	11.742	1.66%

[1] $\% Difference = \frac{80in. - 60in.}{80in.} * 100\%$

Further comparisons for each point of interest were done for each brace stiffness at each brace configuration. Figure 11 displays the distribution of lateral accelerations along the span of the I-joist. The "x" denotes the distance from the end support, while the "L" denotes the span length. In addition, the black vertical lines display where bracing was located. Figure 12 reveals that the 1.2 lb/in. brace stiffness behaved very different from the rest of the brace stiffnesses. This could be due to the springs stiffness combined with the I-joist's stiffness causing a frequency of walking near the I-joist's natural frequency, ultimately causing greater lateral accelerations to occur. The other four brace stiffnesses (zero stiffness, 8.5 lb/in., 14.0 lb/in. and infinitely stiff) followed an inverse relationship between brace stiffness and lateral acceleration that was expected: as the brace stiffness increased, the lateral acceleration decreased. This trend can also be observed in Table 3. The only location along the I-joist where this trend does not occur is at position 0.125. This could have been due to the stiffness of the end support or test subjects could have caused larger lateral accelerations for some unknown reason.

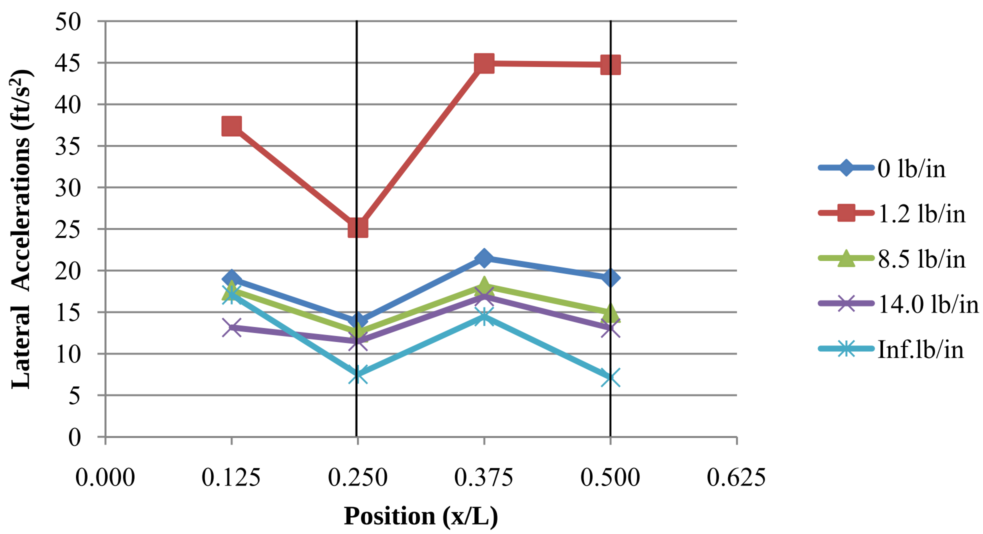

Figure 11: Lateral Accelerations for the 60 in. Brace Configuration

Figure 12 shows the results for the 80 in. brace configurations and is constructed the same as Figure 11. Figure 12 reveals the same trend as earlier: as brace stiffness increased, lateral accelerations decreased. However, for the 80 in. brace configuration, the 1.2 lb/in. brace stiffness follows this trend except at the position 0.33. As in Figure 11, Figure 12 displays an increase in lateral acceleration for the 1.2 lb/in. brace stiffness. The lateral accelerations of the other four brace stiffnesses decreased at the braced point. As noted earlier, this change in behavior could be due the combination of the brace stiffness and I-joist stiffness. For the two configurations, the infinitely stiff bracing obtained the lowest lateral accelerations with the exception of the 0.33 point closest to the support.

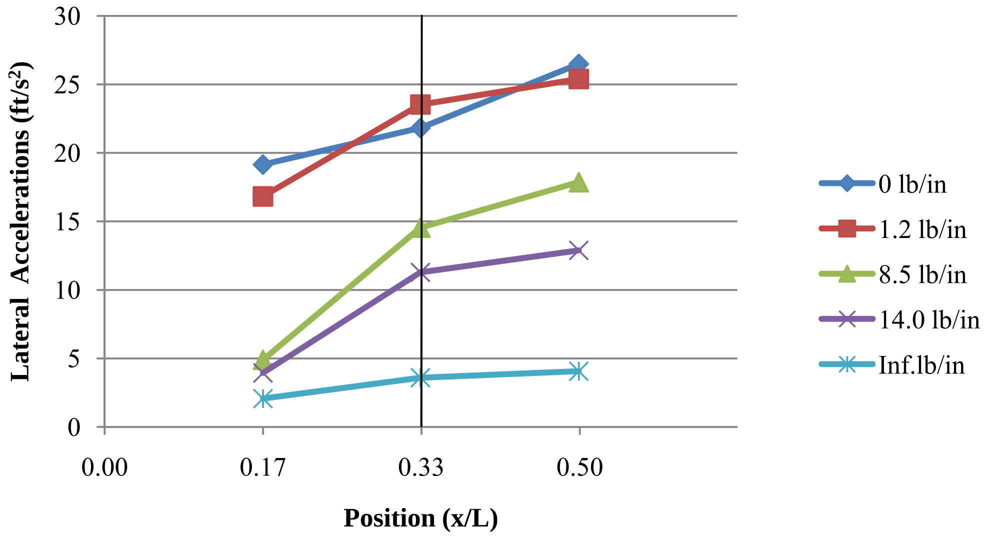

Figure 12: Lateral Accelerations for the 80 in. Brace Configuration

4.2.2 Lateral Displacements

Further comparisons were performed for the lateral displacements of the I-joist, and the tables and graphs were constructed the same as the lateral accelerations. The lateral displacement data was extracted from the string potentiometers that were attached to the top flange only. Table 4 displays the average of the lateral displacements for each bracing configuration, as well as the percent differences between them. The largest percent difference occurred with the 1.2 lb/in. brace stiffness, while the infinitely stiff brace stiffness had the second highest percent difference. Table 4 reveals the same inverse relationship for both brace configurations between brace stiffness and lateral displacement: as brace stiffness increased, lateral displacement decreased. This is a relationship that was expected and correlated with lateral stability and bracing fundamentals. Another observation is the percent difference is approximately equal for the zero stiffness bracing for the two brace configurations. The string potentiometers' did not affect the I-joist's lateral displacement and the two groups of test subjects appear to behave very similar.

Table 4: Evaluation of Lateral Displacements for Both Brace Configurations at Each Brace Stiffness

60 in. Brace Configuration		80 in. Brace Configuration		% Difference[1]
Stiffness (lb/in)	Average (in)	Stiffness (lb/in)	Average (in)	
0.0	1.332	0.0	1.327	-0.38%
1.2	0.847	1.2	0.988	14.26%
8.5	0.613	8.5	0.652	6.10%
14.0	0.548	14.0	0.542	-1.17%
∞	0.336	∞	0.364	7.66%

[1] $\% \, Difference = \frac{80in.-60in.}{80in.} * 100\%$

To further compare the different brace configurations for lateral displacement, Figures 13 and 14 were constructed. These figures were constructed the same as the lateral acceleration graphs with respect to the x-axis orientation and the vertical lines denoting where bracing was located. Both graphs reveal the same trend that Table 4 revealed earlier: as brace stiffness increased, lateral displacement decreased. The bracing of the compression flange is vital to reduced beam lateral displacement (Yura 2001). Another trend these graphs reveal is the parabolic relationship between lateral displacement and location, and that the largest lateral displacement occurs at mid-span. In addition, as the location of the span nears the mid-span, the lateral displacement nears its maximum and the slope of the graph approaches zero. This reveals that the lateral displacement behavior is symmetrical about the mid-span of the I-joist.

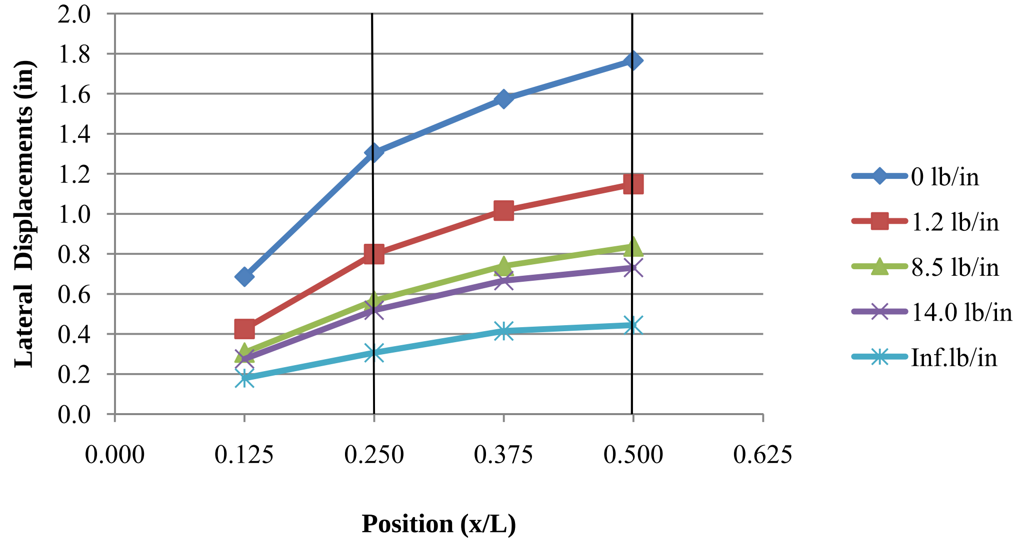

Figure 13: Lateral Displacements for the 60 in. Brace Configuration

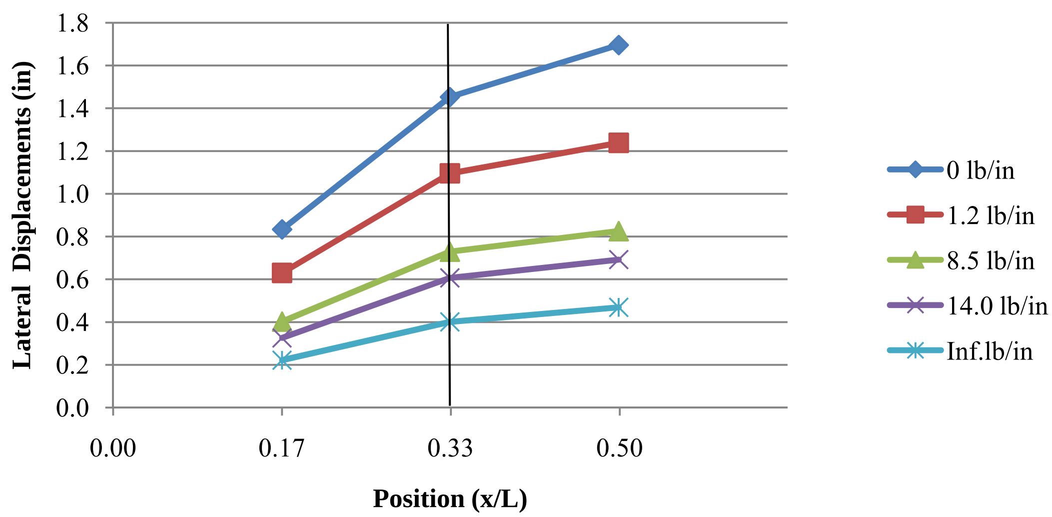

Figure 14: Lateral Displacements for the 80 in. Brace Configuration

4.2.3 Twist

Further comparisons were completed for the twist of the I-joist, and the tables and graphs used for these comparisons were constructed in the same as the lateral accelerations and displacements. The twist of the I-joist was calculated using the top flange and bottom flange string potentiometer data. For calculations, it was assumed that the web did not deform and remained at a constant depth of 16 in. This allowed for the use of a trigonometric function to find the angle the I-joist rotated. Since the string potentiometers were 1 in. above and below the flanges, a depth of 18 in. was used for calculations. Table 5 displays the averages of the twist for each bracing configuration, as well as the percent differences between them. The largest percent difference occurred at the infinitely stiff bracing and the second largest percent difference occurred at the 1.2 lb/in. brace stiffness. None of the percent differences were negative, indicating that the 60 in. brace configuration always had a smaller twist than the 80 in. brace configuration. Therefore, the 60 in. brace configuration had an increased amount of bracing and reduced twist. Another trend that is observed is the inverse relationship between brace stiffness and twist: as brace stiffness increased, twist decreased. This is a trend that has been observed for all three dependent variables.

Table 5: Evaluation of Twist for Both Brace Configurations at Each Brace Stiffness

60 in. Brace Configuration		80 in. Brace Configuration		% Difference[1]
Stiffness (lb/in)	Average (deg)	Stiffness (lb/in)	Average (deg)	
0.0	3.364	0.0	3.790	11.24%
1.2	2.426	1.2	2.856	15.05%
8.5	1.960	8.5	2.165	9.46%
14.0	1.760	14.0	1.910	7.86%
∞	1.112	∞	1.370	18.84%

[1] $\%\ Difference = \frac{80in. - 60in.}{80in.} * 100\%$

To further analyze the twist, Figures 15 and 16 were constructed so that each point of interest could be analyzed separately for each brace stiffness and configuration. These figures reveal the same inverse relationship that Table 5 revealed: as brace stiffness increased, twist decreased. Figures 15 and 16 correlate with Yura (2001), noting the reduction of twist from compression flange bracing. These graphs also display the parabolic relationship between twist and position, as well as the maximum twist occurring at mid-span. For both configurations, the slope approaches zero as it nears mid-span which reveals that the twist behavior is symmetrical about the mid-span of the I-joist.

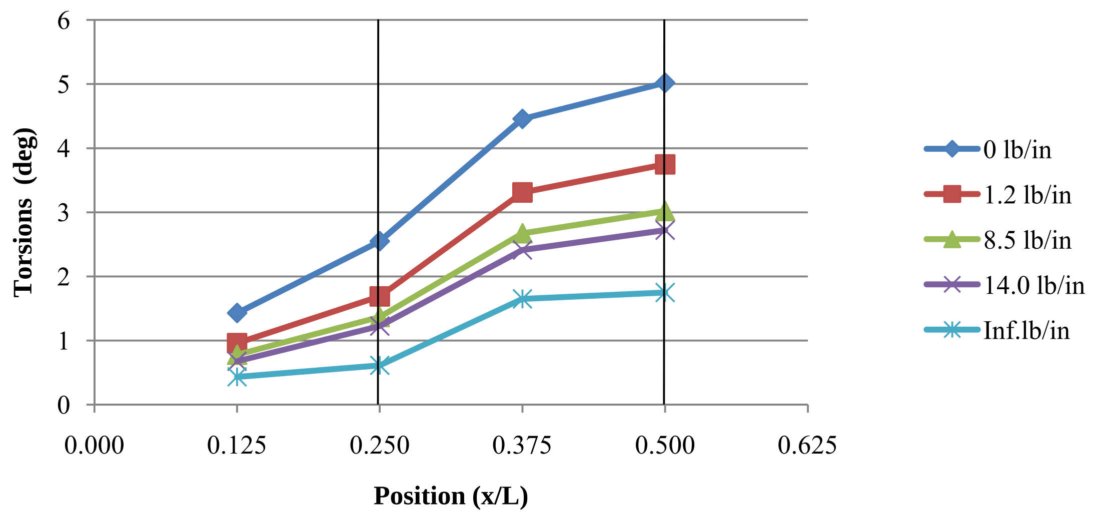

Figure 15: Twists for the 60 in. Brace Configuration

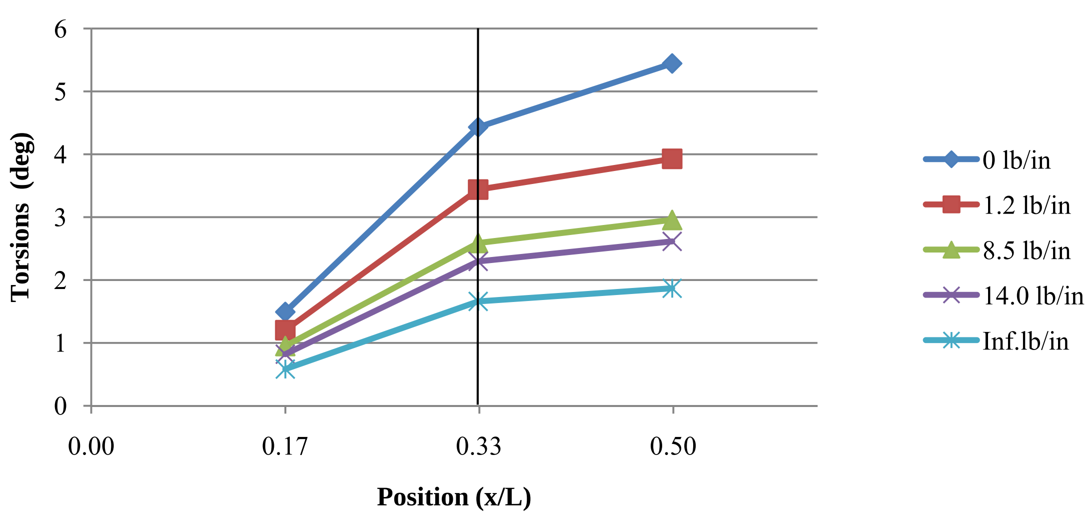

Figure 16: Twists for the 80 in. Brace Configuration

4.2.4 Comparison of Both Brace Configurations Using All Five Brace Stiffnesses

In this section, the two different brace configurations were compared to each other. All three dependent variables were analyzed separately for each brace configuration, and all five brace stiffnesses were analyzed together. There were a total of 600 data points for the 60 in. brace configuration (200 for each dependent variable) and 450 data points for the 80 in. brace configuration (150 for each dependent variable). Table 6 displays the results of the numerical evaluation of the raw data, aw well as the statistical analysis results for each dependent variable. The largest percent difference occurred between the two configurations for the twist, with lateral accelerations having a similar percent difference. The large percent difference between the two configurations is probably due to the 1.2 lb/in. brace stiffness having larger values and increasing the average of the 60 in. brace configuration. In addition, the percent difference is negative, indicating that the 60 in. brace configuration had larger lateral accelerations.

The statistical analysis revealed that brace configuration was not statistically significant for either lateral accelerations or lateral displacements, but was statistically significant for twist (p = 0.016). In addition, twist had the largest percent difference between the two configurations.

Table 6: Evaluation of Both Brace Configurations for all Brace Stiffnesses (significant results are highlighted)

Lateral Accelerations		Lateral Displacements		Twists	
Spacing (in)	Average (ft/s^2)	Spacing (in)	Average (in)	Spacing (in)	Average (deg)
60	19.488	60	0.735	60	2.124
80	17.398	80	0.775	80	2.418
% Difference[1]	-12.00%	% Difference[1]	5.09%	% Difference[1]	12.15%
p-Value	0.954	p-Value	0.207	p-Value	0.016

[1] $\% \; Difference = \frac{80in. - 60in.}{80in.} * 100\%$

4.2.5 Comparison of Both Brace Configurations at Each Brace Stiffness

Once the comparison of the different brace configurations was completed using all five brace stiffnesses, analysis of the different brace configurations for each individual brace stiffness was performed so that comparisons could be made between the brace stiffnesses. Table 7 displays the statistical analysis results for all three dependent variables. For each brace stiffness there were a total of 40 data points in the 60 in. brace configuration and 30 data points for each brace stiffness in the 80 in. brace configuration, for each dependent variable.

Table 7: Statistical Comparison of Both Brace Configurations at Each Brace Stiffness (significant results are highlighted)

Lateral Accelerations		Lateral Displacements		Twists	
Stiffness (lb/in)	*p*-Value	Stiffness (lb/in)	*p*-Value	Stiffness (lb/in)	*p*-Value
0.0	0.360	0.0	0.940	0.0	0.567
1.2	0.012	1.2	0.053	1.2	0.018
8.5	0.928	8.5	0.262	8.5	0.079
14.0	0.272	14.0	0.708	14.0	0.118
∞	0.311	∞	0.029	∞	< 0.001

For lateral accelerations and twist, the 1.2 lb/in. brace stiffness was statistically significant between the two brace configurations, and borderline for lateral displacements (p = 0.053). Infinitely stiff bracing was significant for lateral displacements and twist. As the brace stiffness approaches infinity, increased stiffness significantly reduced the lateral displacement and twist. Since the twist had two significant ($p < 0.05$), the assumption made earlier that an increased amount of bracing does have a significant effect on reducing the twist can be confirmed.

4.3 Points of Interest Comparisons

This section will compare and discuss the different points of interest using the lateral acceleration measurements of the I-joist. A "point of interest" refers to as a point where mechanical behaviors were recorded during testing and are displayed in Figure 10 for each brace configuration. The points of interest were divided into two different groups for analysis: with bracing and without bracing.

Analysis was not performed for lateral displacement and twist. Figures 14, 15, 16 and 17 displayed a parabolic relationship and revealed that the point near the support will significantly reduce the average of the points where no bracing is present. In addition, since the point of greatest lateral displacement and twist occurred at mid-span, this point cannot be compared to another point close to the end support. Because the positions examined on the I-joist were different for each brace configuration, an analysis was not performed on the same position of the beam for the two brace configurations for lateral displacement and twist. However, the data did not display a parabolic relationship for the lateral accelerations. In fact, Figures 11 and 12 display a more sinusoidal relationship with the greater magnitudes occurring at the points where bracing was not present. Comparisons could be made between the two different groups of points, as well as the two brace configurations.

4.3.1 Comparison of Each Brace Stiffness with Both Brace Configurations

In this section, a comparison of each brace stiffness with both brace configurations was completed. This comparison provided a perspective to understand if the stiffness was a sole cause of any significance between the two groups. Table 8 displays the numerical and statistical results of the analysis. The 1.2 lb/in. brace stiffness had the lowest percent difference of -0.07% (p = 0.994), and the lateral accelerations were approximately equal to each other. There was no difference between a point with bracing and a point without bracing for the 1.2 lb/in. brace stiffness. The zero stiffness, 8.5 lb/in. and 14.0 lb/in. brace stiffness all had percent differences around 15% ($p > 0.05$). There were no significant differences between points with bracing and points without bracing for these three stiffnesses.

The infinitely stiff bracing stiffness had the largest percent difference of 43.99% ($p < 0.001$). The infinitely stiff bracing did have a statistically significant effect on points with bracing compared with points without bracing. The percent difference was positive, indicating that the lateral acceleration of points without bracing were greater than lateral acceleration of points with bracing. The same trend was observed for all stiffnesses, excluding the 1.2 lb/in. brace stiffness, and shows that bracing does reduce the lateral acceleration at points with bracing. The bracing may act to disperse the accelerations to the adjacent I-joist or the springs could be absorbing energy from the I-joist's movement, because, as the brace stiffness increased, that lateral accelerations decreased.

Table 8: Evaluation of Lateral Accelerations at Different Points of Interest for Each Brace Stiffnes with Both Brace Configurations (significant results are highlighted)

Stiffness (lb/in)	Point of Interest	Lateral Accelerations (ft/s^2)	% Difference[1]	*p*-Value
0.0	No Bracing	21.529	15.15%	0.145
0.0	Bracing	18.268		
1.2	No Bracing	30.119	-0.07%	0.994
1.2	Bracing	31.142		
8.5	No Bracing	16.411	14.44%	0.235
8.5	Bracing	14.039		
14.0	No Bracing	15.138	16.71%	0.082
14.0	Bracing	12.608		
∞	No Bracing	14.383	43.99%	< 0.001
∞	Bracing	8.058		

[1] $\% \, Difference = \frac{No\ Bracing - Bracing}{No\ Bracing} * 100\%$

Another important observation from Table 8 was the 1.2 lb/in. brace stiffness has a negative percent difference, meaning the points with bracing had a larger lateral acceleration than points without bracing. This phenomenon could be due to the energy of the spring inducing more energy in the I-joist than is being transferred to other I-joists. An important factor that was observed during testing was as the spring stiffness increased, the I-joists moved in relation to each other more. Whereas, when the brace stiffness was lower (1.2 lb/in.), the two outside I-joists moved in the opposite lateral direction as the middle I-joist. This change in behavior may signify a different transfer of energy through the braces caused by a natural frequency of the system. For the 1.2 lb/in. brace stiffness, the springs were being compressed and stretched more than the other springs and exuding more energy on the I-joist. This was only an observation and no numerical value is known for how much the spring actually deflected. The energy for a spring is displayed in Equation 2.

$$E = \frac{1}{2} * k * l^2 \qquad (2)$$

where,

E = energy from the spring

k = stiffness of the spring

l = deflection of the spring

Equation 5 reveals that the amount of energy a spring possesses is directly related to the square of its deflection. Since the 1.2 lb/in. brace is believed to have deflected more than the other springs, more energy would have been applied to the I-joist. This increase in energy could have been the cause of the 1.2 lb/in. brace to have a greater affect on the lateral accelerations. Another assumption could be that the energy from the springs combined with the energy of the string potentiometers could have caused a harmonic motion which increased the amount of lateral acceleration.

4.3.2 Comparison of Both Brace Configurations for Each Brace Stiffness

Once the comparison of the brace stiffnesses with both brace configurations was completed, a comparison was performed to analyze both brace configurations separately for each brace stiffness. This provided a more narrow view to see which brace configuration or stiffness had a significant affect on the I-joist's lateral accelerations. Tables 9 and 10 display the numerical and statistical results of the analysis.

Table 9 displays the results for the 60 in. brace configuration, and reveals that the infinitely stiff bracing had the largest percent difference of 53.49% ($p < 0.001$) and reveals there is significance between points with and without bracing for this stiffness. The other four stiffnesses had percent differences that ranged from 15.03% to 23.06% ($p > 0.05$). In addition, the 1.2 lb/in. brace stiffness had a positive percent difference, which means that points without bracing had higher lateral accelerations than the points with bracing. This correlates with Figure 12 which displays the largest lateral accelerations occurring at points without bracing. However, this finding does not correlate with the previous section, but reveals that negative percent calculated in the previous section is a result of the 80 in. brace configuration's behavior and can be seen in Table 10.

Table 9: Evaluation of Lateral Accelerations at Different Points of Interest for the 60 in. Brace Configuration for Each Brace Stiffness (significant results are highlighted)

Stiffness (lb/in)	Point of Interest	Lateral Accelerations (ft/s^2)	% Difference[1]	p-Value
0.0	No Bracing	20.236	18.50%	0.072
0.0	Bracing	16.493		
1.2	No Bracing	41.135	15.03%	0.063
1.2	Bracing	34.951		
8.5	No Bracing	17.894	23.06%	0.097
8.5	Bracing	13.770		
14.0	No Bracing	15.010	18.20%	0.152
14.0	Bracing	12.280		
∞	No Bracing	15.764	53.49%	< 0.001
∞	Bracing	7.333		

[1] $\% \, Difference = \frac{No \; Bracing - Bracing}{No \; Bracing} * 100\%$

Table 10 displays the results of the 80 in. brace configuration. For the 1.2 lb/in., there is a negative percent difference of -11.48% which means that the points with bracing experienced larger lateral accelerations than points without bracing. This could be due the energy of the spring acting on the I-joist or the dynamic load creating a natural frequency in the braced system as explained in the previous section. In addition, the infinitely stiff brace stiffness had the largest percent difference of 26.88% (p = 0.127). There is no significance between the two groups of points for the 80 in. brace configuration; however the points without bracing had larger lateral accelerations than points with bracing. This trend was also the case for the other four brace stiffnesses (p > 0.05). In conclusion, there was no significance between the points with and without bracing, but the points with bracing were smaller than points without bracing except for the 1.2 lb/in. brace stiffness at the 80 in. brace configuration.

Table 10: Evaluation of Lateral Accelerations at Different Points of Interest for the 80 in. Brace Configuration for Each Brace Stiffness

Stiffness (lb/in)	Point of Interest	Lateral Accelerations (ft/s^2)	% Difference[1]	p-Value
0.0	No Bracing	22.822	4.40%	0.858
0.0	Bracing	21.818		
1.2	No Bracing	21.206	-11.48%	0.374
1.2	Bracing	23.527		
8.5	No Bracing	14.925	2.30%	0.984
8.5	Bracing	14.583		
14.0	No Bracing	15.266	13.08%	0.543
14.0	Bracing	13.268		
∞	No Bracing	13.002	26.88%	0.127
∞	Bracing	9.508		

[1] $\% \ Difference = \frac{No\ Bracing - Bracing}{No\ Bracing} * 100\%$

4.4 Brace Stiffness Comparison with Respect to Zero Stiffness

This section discusses the I-joist behavior for each brace stiffness relative to the behavior of the zero brace stiffness (control). This will reveal the contribution of the brace stiffness to the movement of the I-joist. All three dependent variables are discussed and compared individually.

4.4.1 Lateral Accelerations

Table 11 displays the percent differences between each brace stiffness at a specified point of interest compared to the zero stiffness behavior, and the highlighted rows denote points with bracing. For the 1.2 lb/in. brace stiffness, all the percent differences are negative for the 60 in. brace configuration and negative at the point with bracing for the 80 in. brace configuration. The 1.2 lb/in. brace stiffness increased the lateral accelerations throughout the span of the I-joist for the 60 in. brace configuration and at the point with bracing for the 80 in. brace configuration. This correlates with Figures 11 and 12, which show similar behavior indicating that a natural frequency for this particular brace stiffness and configuration may have been found (Chopra 2007). For the 8.5 lb/in. brace stiffness, the percent difference increases as the position approaches mid-span for the 60 in. brace configuration but stays almost constant throughout the span for the 80 in. brace configuration. The increased amount of bracing decreased the lateral accelerations by a greater magnitude as the position approached mid-span but decreased the lateral accelerations by about the same magnitude throughout the span with less bracing. The increased stiffness did lead to reduced lateral accelerations.

Table 11: Evaluation of Lateral Accelerations at Specified Points of Interest for Each Brace Stiffness Relative to Zero Brace Stiffness

	Position (x/L)	Brace Stiffness (lb/in)			
		1.2	8.5	14.0	∞
60 in. Brace Config-uration	0.125	-96.93%	7.03%	30.69%	10.08%
	0.250	-81.44%	9.25%	17.17%	45.78%
	0.375	-108.86%	15.59%	21.53%	32.70%
	0.500	-133.99%	21.79%	31.63%	62.63%
80 in. Brace Config-uration	0.167	12.17%	35.90%	34.27%	33.78%
	0.333	-7.84%	33.16%	39.18%	56.42%
	0.500	4.16%	33.65%	32.25%	49.70%

$$\% \, Difference = \frac{Zero \; Brace \; Stiffness - Brace \; Stiffness.}{Zero \; Brace \; Stiffness} * 100\%$$

For the 14.0 lb/in. brace stiffness, the percent differences are sporadic for the 60 in. brace configuration, but are almost constant for the 80 in. brace configuration. The percent difference is greatest at the bracing location for the 80 in. brace configuration. The percent differences are larger for the 14.0 lb/in. brace stiffness than for the 8.5 lb/in. brace stiffness and reveal the same trend that has been observed throughout the analysis: as brace stiffness increased, lateral acceleration decreased. For the infinitely stiff brace stiffness, the percent differences are the largest at points with bracing. In addition, the percent differences are larger at most of the points of interest for the infinitely stiff brace stiffness than for the 14.0 lb/in. brace stiffness. The only location the percent differences are not greater is at the location closest to the support and it is uncertain why this occurred.

Table 12 displays the results of the statistical analysis, as well as the percent differences, to observe which brace stiffness had a significant affect on the I-joist's lateral acceleration relative to the zero stiff brace stiffness. For the 60 in. brace configuration, all four stiffness were statistically significant. The 1.2 lb/in. brace stiffness had the largest percent difference of -107.15%, which means the brace stiffness more than doubled the lateral accelerations relative to the zero stiffness. The other three brace stiffnesses' percent differences increased as the stiffness increased and correlated with previous observations. For the 80 in. brace configuration, the 1.2 lb/in. brace stiffness had lowest percent difference of 2.55% and was the only stiffness that was not statistically significant (p = 0.696). However, the other three stiffnesses were all statistically significant and reveal the same trend as the 60 in. brace configuration: as brace stiffness increased, lateral displacement decreased.

Table 12: Evaluation of Lateral Accelerations at Each Brace Stiffness Relative to Zero Brace Stiffness for Each Brace Configuration (significant results are highlighted)

Stiffness (lb/in)	60 in. Brace Configuration		80 in. Brace Configuration	
	p-Value	% Difference[1]	p-Value	% Difference[1]
1.2	< 0.001	-107.15%	0.696	2.55%
8.5	0.034	13.80%	0.001	34.13%
14.0	< 0.001	25.70%	< 0.001	35.07%
∞	< 0.001	37.12%	< 0.001	47.36%

[1] $\% \, Difference = \frac{Zero\ Brace\ Stiffness - Brace\ Stiffness}{Zero\ Brace\ Stiffness} * 100\%$

4.4.2 Lateral Displacements

Table 13 displays the percent differences for each brace stiffness at a specified point of interest to the zero stiffness behavior, and is constructed the same as Table 12. The percent differences are almost constant throughout the span for each brace stiffness and configuration. However, for the 60 in. brace configuration, the largest percent difference always occurred at position 0.250. For the 80 in. brace configuration, the largest percent difference occurred at position 0.167 except for the 1.2 lb/in. brace stiffness which occurred at position 0.500. The percent differences are about equal with the 60 in. brace configuration being slightly larger at each stiffness except for the 1.2 lb/in. brace stiffness. For the 1.2 lb/in. brace stiffness, the 60 in. brace configuration had much larger percent differences than for the 80 in. brace configuration. An increased amount of bracing reduced the amount of lateral displacement but once the stiffness increased, there was very little difference between the two configurations. Another trend that is observed from Table 13 is that the percent difference increased as the brace stiffness increased, which is consistent throughout the span of the I-joist. This correlates with previous observations and can be observed in Figures 13 and 14.

Table 13: Evaluation of Lateral Displacements at Specified Points of Interest for Each Brace Stiffness Relative to Zero Brace Stiffness

	Position x/L	Brace Stiffness (lb/in)			
		1.2	8.5	14.0	∞
60 in. Brace Configuration	0.125	37.98%	55.20%	59.84%	73.79%
	0.250	38.79%	56.61%	60.25%	76.56%
	0.375	35.40%	52.97%	57.63%	73.64%
	0.500	34.97%	52.57%	58.58%	74.85%
80 in. Brace Configuration	0.167	24.43%	51.71%	60.90%	73.38%
	0.333	24.58%	49.80%	58.23%	72.38%
	0.500	26.97%	51.32%	59.18%	72.35%

$$\% \, Difference = \frac{Zero\ Brace\ Stiffness - Brace\ Stiffness.}{Zero\ Brace\ Stiffness} * 100\%$$

Table 14 displays the results of the statistical analysis as well as the percent differences between designated brace stiffness relative to zero brace stiffness. All four brace stiffnesses for both brace configurations are statistically significant and the percent differences increase as the brace stiffness increases and correlates with previous observations made from Table 13. In addition, all percent differences are larger for the 60 in. brace configuration at each stiffness and are much larger for the 1.2 lb/in. brace stiffness. This alludes to the conclusion that an increased amount of bracing reduced lateral displacement but once the stiffness increased, the amount of bracing does not have as large of an affect. Also, a trend was observed that was noted earlier: as the brace stiffness increased, the lateral displacement decreased. The stiffness of the brace controls the magnitude of the lateral displacements. The reduction of lateral displacement was due to the brace being located on the compression flange. The compression flange is where lateral movement occurs, so bracing this section of the I-joist is crucial in reduction of movement (Hindman et al. 2005a).

Table 14: Evaluation of Lateral Displacements at Each Brace Stiffness Relative to Zero Brace Stiffness for Each Brace Configuration (significant results are highlighted)

Stiffness (lb/in)	60 in. Brace Configuration		80 in. Brace Configuration	
	p-Value	% Difference[1]	p-Value	% Difference[1]
1.2	< 0.001	36.42%	< 0.001	25.57%
8.5	< 0.001	54.02%	< 0.001	50.85%
14.0	< 0.001	58.87%	< 0.001	59.19%
∞	< 0.001	74.77%	< 0.001	72.58%

[1] $\% \, Difference = \frac{Zero\ Brace\ Stiffness - Brace\ Stiffness}{Zero\ Brace\ Stiffness} * 100\%$

4.4.3 Twist

Table 15 displays the percent differences for each brace stiffness at a specified point of interest relative to the zero brace stiffness behavior, and is constructed the same as Tables 11 and 13. Percent differences are larger for the 60 in. brace configuration than the 80 in. brace configuration for all four brace stiffnesses and shows that an increased amount of bracing reduced the twist of the I-joist. The percent differences also display an increase as the position approaches mid-span for the 80 in. brace configuration. For the 60 in. brace configuration, the percent differences decrease as the position approaches mid-span and reaches the greatest percent difference at position 0.250. This peak in percent difference also occurred for the lateral displacements and could be due to increased stiffness closer to the support causing an increase in stiffness at the support or the load being transferred to adjacent I-joists and their end supports. Another common trend is that the percent differences increase as the stiffness increases. All of the percent differences are positive and allude to the inverse relationship: as brace stiffness increased, twist decreased.

Table 15: Evaluation of Twist at Specified Points of Interest for Each Brace Stiffness Relative to Zero Brace Stiffness

	Position x/L	Brace Stiffness (lb/in)			
		1.2	8.5	14.0	∞
60 in. Brace Configuration	0.125	32.90%	45.42%	52.55%	69.59%
	0.250	33.73%	46.30%	51.87%	75.90%
	0.375	25.74%	40.04%	45.87%	63.00%
	0.500	25.35%	39.84%	45.77%	65.14%
80 in. Brace Configuration	0.167	19.40%	36.38%	44.99%	60.94%
	0.333	12.50%	41.57%	48.19%	62.57%
	0.500	27.86%	45.70%	52.01%	65.68%

$$\% \, Difference = \frac{Zero\ Brace\ Stiffness - Brace\ Stiffness.}{Zero\ Brace\ Stiffness} * 100\%$$

Table 16 displays the results of the statistical analysis as well as the percent differences between specified brace stiffness relative to zero brace stiffness. All four brace stiffnesses for both brace configurations are statistically significant. For both brace configurations, the percent difference increased as brace stiffness increased. This trend correlates with the trend found with lateral displacements and in Table 15, and was due to bracing of the compression flange. Since this experiment focused on bending, flexure and twist were considered for bracing requirements (Yura 2001). By bracing the compression flange and, as the brace stiffness increased, the amount of lateral displacement and twist was decreased.

Table 16: Evaluation of Twist at Each Brace Stiffness Relative to Zero Brace Stiffness for Each Brace Configuration (significant results are highlighted)

Stiffness (lb/in)	60 in. Brace Configuration		80 in. Brace Configuration	
	p-Value	% Difference[1]	p-Value	% Difference[1]
1.2	< 0.001	27.87%	< 0.001	24.64%
8.5	< 0.001	41.72%	< 0.001	42.87%
14.0	< 0.001	47.68%	< 0.001	49.60%
∞	< 0.001	66.94%	< 0.001	63.85%

[1] $\% \, Difference = \frac{Zero\ Brace\ Stiffness - Brace\ Stiffness}{Zero\ Brace\ Stiffness} * 100\%$

4.5 Test Subjects Weight Comparison

In this section the test subjects' weights were compared to the three mechanical behaviors. An ANCOVA was completed to determine if the weight of a test subject affected the behavior of the I-joist. The test subjects' weights varied from 135 lbs to 218 lbs, with a majority of the subjects being approximately 180 lbs to 190 lbs. Lateral accelerations were not statistically significant (p = 0.596). However, lateral displacement and twist were statistically significant (p = 0.027 and p = 0.022, respectively). Weight had a significant affect on lateral displacements and twist but not on lateral accelerations.

Figures 18, 19 and 20 display all the data gathered for all three mechanical behaviors graphed with the weight of each test subject. Each figure has a total of 350 data points. Figure 18 displays the distribution of the lateral accelerations with respect to the test subjects' weights. The heavier test subjects have larger outlying points. These outlying points are from the 1.2 lb/in. brace stiffness at the 60 in. brace configuration. These outlying points are not sufficient enough to prove that weight has a significant affect on lateral acceleration since the rest of the data points do not vary much as the test subjects' weights increase. In addition, Figure 19 displays the distribution of lateral displacements with respect to the test subjects' weights. As the test subjects' weight increased, the I-joist experienced larger lateral displacements. Figure 20 displays the distribution of twist with respect to the test subjects' weights and is almost identical to Figure 19. This increase in weight (load) causing greater lateral displacements and twist correlates with basic beam theory.

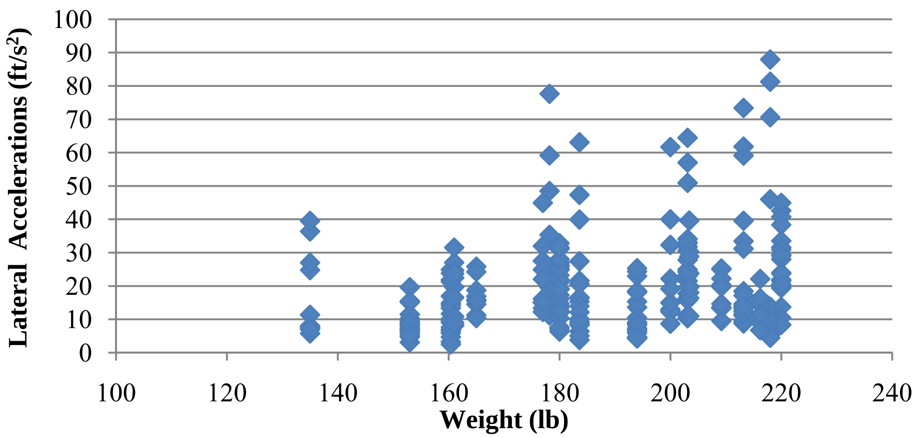

Figure 17: Comparison of Lateral Displacements and Subjects' Weight

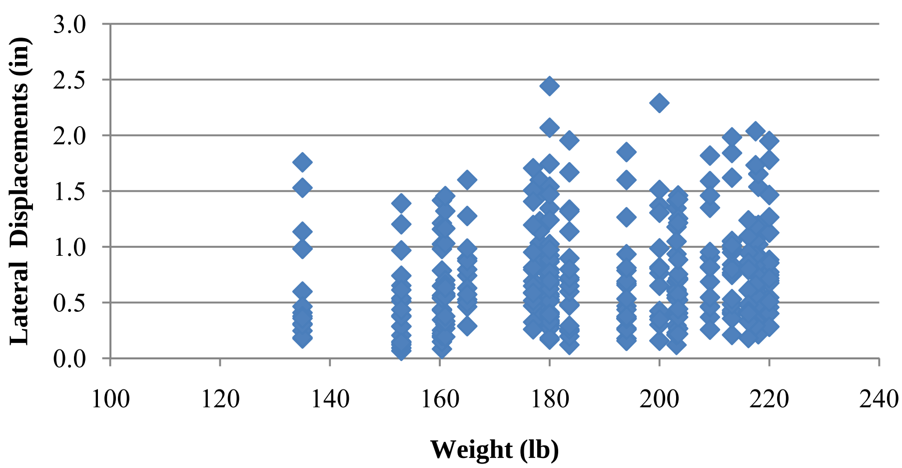

Figure 18: Comparison of Lateral Displacements and Subjects' Weight

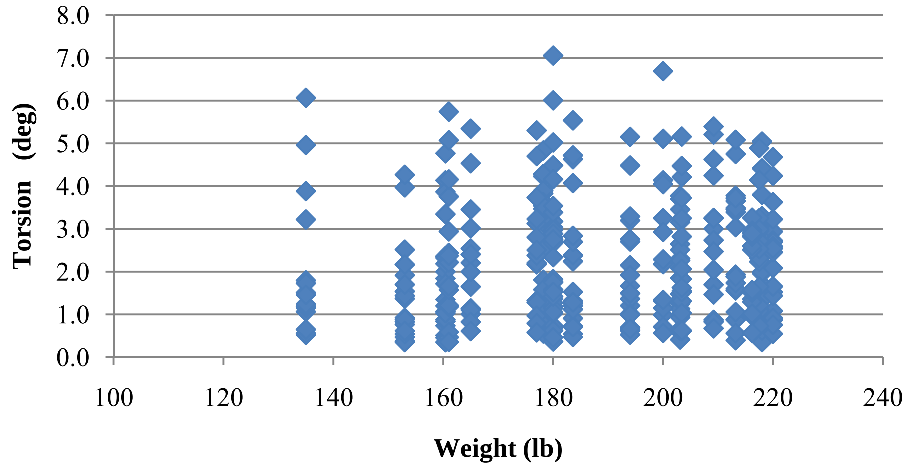

Figure 19: Comparison of Twist and Subjects' Weight

4.6 Test Subjects Occupation Comparison

Another comparison was performed which compared the three mechanical behaviors with respect to the subjects' occupation. The subjects' occupations were comprised of students and construction workers. Each test configuration had ten test subjects, consisting of seven students and three construction workers. This yielded a total of fourteen students and six construction workers for the entire experiment. Statistical analysis was performed and Table 18 displays the results. Table 18 reveals that all three mechanical behaviors were not statistically significant ($p > 0.05$). However, lateral accelerations had percent difference of 24.71% which was much larger than the percent difference for lateral displacements and twist, 11.25% and 8.98%, respectively. This larger percent difference was due to the outlying points obtained from the 1.2 lb/in. brace stiffness for the 60 in. brace configuration. In addition, during testing one of the accelerometers broke and reduced the number of readings obtained for the construction workers. This reduction in the amount of data points, with a combination of small sample size, could have had an affect on the statistical analysis

Table 17: Evaluation of Test Subjects Occupation

	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
Students	6.087	0.777	2.307
Construction Workers	4.583	0.689	2.100
% Difference[1]	24.71%	11.25%	8.98%
p-Value	0.179	0.300	0.208

[1] $\% \, Difference = \frac{Student - Construction\,Worker}{Student} * 100\%$

Further analysis showed differences between the two occupations with the students producing a greater magnitude for all three dependent variables. In addition, one important observation during testing was the construction workers felt more comfortable walking on the I-joists and did not have a problem walking to the beat of 45 beats per second produced by the metronome. However, the students showed a lack of comfort walking on the I-joists. When a student began to lose their balance, they immediately grabbed the hand rails and did not walk to the beat. Some of the students said on the questionnaire that walking to the beat was the most difficult part of the experiment. They proclaimed it was difficult to concentrate on their balance and walking speed simultaneously. Some students wore construction boots and claimed these shoes provided them with more balance. Construction boots do provide more ankle support, but this could have been more psychological for the students who wore them. The construction workers produced smaller magnitudes for each dependent variable because they were more comfortable walking on the I-joists. Statistically there was no significant difference between students and construction workers, but there was a comparative difference between the averages of the two occupations.

Chapter 5: Summary and Conclusions

5.1 Summary

This research studied the lateral behavior of unbraced wood composite I-joists dynamically loaded by human test subjects. The I-joist lateral acceleration, lateral displacement and twist were recorded as human test subjects walked across the I-joist with different bracing configurations and stiffnesses. Two bracing configurations consisting of one-quarter and one-third spacings of the span length, 60 in. and 80 in. respectively, were used. Brace stiffnesses consisted of 0 lb/in., 1.2 lb/in., 8.5 lb/in., 14.0 lb/in. and an infinitely stiff. In addition, test subjects occupations and weights were recorded. Two occupations of test subjects were students and construction workers, while the test subjects' weights varied from 135 lbs to 218 lbs.

5.2 Conclusions

The first specific goal of this research project was to analyze the relationships of lateral acceleration, lateral displacement and twist with respect to the brace configuration. The research concluded that brace configuration did not have an affect on lateral accelerations. However, for the lateral displacements and twists, the 60 in. brace configuration had smaller responses. The second specific objective of this research project was to analyze the relationships of lateral acceleration, lateral displacement and twist with respect to the brace stiffness. The research concluded that for all three behaviors, increased brace stiffness reduced the amount of response. In addition, an inverse relationship between response and brace stiffness occurred throughout the experiment: as brace stiffness increased, lateral displacement and twist decreased. This trend was observed for lateral accelerations with the exception of the 1.2 lb/in. brace stiffness.

The following trends were observed for the three mechanical behaviors throughout the analysis and appropriate conclusions were drawn from this research project:

5.2.1 Lateral Accelerations

- The 1.2 lb/in. brace stiffness for the 60 in. brace configuration produced accelerations that were much higher than the other four brace stiffnesses. This was either due to the spring deflecting more and, therefore, applying more energy to the I-joist or a natural frequency was found during testing.
- There was no significant difference between points with bracing with respect to point without bracing except for the infinitely stiff brace stiffness at the 60 in. brace configuration.
- Excluding the 1.2 lb/in. brace stiffness, as the brace stiffness increased the lateral acceleration significantly decreased.
- The test subjects' weights did not have a significant effect on the I-joist's lateral acceleration, but the heavier subjects did induce a very small increase in lateral accelerations.
- The test subjects' occupations did not have a significant effect on the I-joist's lateral acceleration; however, the students did induce larger lateral accelerations.

5.2.2 Lateral Displacements

- As brace stiffness increased, lateral displacement of the I-joist decreased. This was due to bracing of the compression throughout the experiment.
- An increased amount of bracing reduced lateral displacement but once the stiffness increased by so much, the amount of bracing did not have as large of an affect and stiffness began to govern.
- The test subjects' weight had a significant effect on the I-joist's lateral displacements with heavier test subjects inducing larger lateral displacements.

- The test subjects' occupations did not have a significant effect on the I-joist's lateral displacements; however, the students did induce larger lateral displacements.

5.2.3 Twists

- An increased amount of bracing and brace stiffness decreased the amount of twist the I-joist experienced. This was due to bracing the compression flange, which prevented it from buckling and rotating about its longitudinal axis.
- The test subjects' weight had a significant effect on the I-joist's twist with heavier test subjects inducing larger twists.
- The test subjects' occupations did not have a significant effect on the I-joist's twist; however, the students did induce larger twists.

5.3 Limitations

Some limitations of this research project were limited to either materials available or the scope of the project. The materials that limited the project were the number of available string potentiometers and accelerometers, which limited the amount of points along the I-joist that could be analyzed. The scope of the research project provided the following limitations:

- Only the lateral direction of the I-joist was recorded and analyzed.
- Only one I-joist was instrumented for testing. This kept the lateral movement of the adjacent I-joists unknown and, therefore, the deflection of the different springs was unknown. There was no way of numerically evaluating how much lateral force or energy was applied to the I-joist.
- Only one type of I-joist was analyzed.
- Only one type of end support was used.
- Only one span length was used.

- The middle I-joist was braced to I-joist with equal stiffness.
- A small population size was examined.

5.4 Recommendations for Future Work

An investigation could be done to further study lean-on bracing for I-joists or more realistic, common bracing used in construction. If the I-joists are laterally connected to a stiffer member, then their lateral movement should be reduced. This could be done by attaching one I-joist or a series of I-joists to a laminated veneer lumber (LVL) beam, an I-joist with wider flanges or any stiffer piece of lumber. Additionally, adjacent member movement should be recorded. This would yield a more acute understanding of how the I-joists react compositely and how the bracing deflections as well. Other materials that could be used for future work would be a variety of I-joist or end supports. Different I-joists with varying dimensions of the flanges and depth could be examined. This would yield better understanding of how the I-joist behaves on its own. In addition, the end supports could be instrumented to determine how much load is being dispersed to adjacent I-joists. End supports could also be instrumented in the lateral direction to observe how much later load is being applied to the I-joists.

The I-joist setup could also be changed. Test subjects could walk perpendicular to the span of the I-joist. This would induce greater lateral loads and create larger lateral displacements and twists. Furthermore, a different range of brace stiffnesses should also be taken into consideration. Rather than increasing from 14.0 lb/in. to infinitely stiff bracing, there should be more of a transition. Moreover, longer or shorter spans could be observed as well, with different brace configuration.

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Appendix A– IRB Approval Memo

VirginiaTech

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FWA00000573(expires 1/20/2010)
IRB # is IRB00000667

DATE: April 8, 2009

MEMORANDUM

TO: Maury A. Nussbaum
Daniel P. Hindman

Approval date: 4/20/2009
Continuing Review Due Date:4/5/2010
Expiration Date: 4/19/2010

FROM: David M. Moore

SUBJECT: **IRB Expedited Continuation 2:** "Investigating Lateral Buckling of Joists as a Cause of Falls from Elevation", CSP #06-0587-09, IRB # 07-234

This memo is regarding the above referenced protocol which was previously granted expedited approval by the IRB. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. Pursuant to your request, as Chair of the Virginia Tech Institutional Review Board, I have granted approval for extension of the study for a period of 12 months, effective as of April 20, 2009.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtain re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

As indicated on the IRB application, this study is receiving federal funds. The approved IRB application has been compared to the OSP proposal listed above and found to be consistent. Funds involving procedures relating to human subjects may be released. Visit our website at www.irb.vt.edu for further information

cc: File
Department Reviewer:Thurmon E. Lockhart
OSP
T. Coalson 0118

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Appendix B– Participant Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: Investigating lateral buckling of joists as a cause of falls from elevation

Investigator: Drs. Daniel P. Hindman and Maury A. Nussbaum

I. Purpose

The long term goal of this project is to reduce the number of falls that occur when a construction worker walks on a joist. A joist (or beam) is a long wooden or composite member, and form the structure of floors and ceilings. When these are unbraced, there is a chance that they may buckle, and a worker subsequently can fall from the joist. In the current study, we wish to measure the loads that are placed on a joist when a worker walks across it. Once we know these loads, we can conduct additional studies to determine when a joist will buckle, as a function of its length, dimensions, and material properties.

II. Procedures

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to collect data that will be used to evaluate and improve the design of a commercial product. Any tasks you perform, or opinions you have will only help us do a better job in this evaluation and design. Therefore, we ask that you perform normally and be as honest as possible. The information and feedback that you provide is very important to this project. The total experiment time will be approximately 1 hour.

During the course of this experiment you will be asked to perform the following tasks:

1) Read and sign an Informed Consent Form (this form).
2) Allow several measures to be obtained from you (e.g. height and weight).
3) Be instructed and view video clips of actual construction tasks.
4) Be fitted with a safety harness.
5) Complete several trials in which you will walk across a joist. During some of these, we will ask you to hold a moderate load (on the order of 20 pounds)

This study will take place within the Brooks Forest Products Center at Virginia Tech.

III. Risks and Benefits

There are minimal risks to you as a participant in this study as follows.

1) You may experience minor muscle strain as a result of performing the experimental tasks.
2) You may experience some muscle soreness, 1-2 days after the experiment.
3) The joists may buckle while you walk across them. To minimize the risk of injury to you, we will require that you wear the safety harness. It is firmly attached to the ceiling, so that if the

joist does buckle, it will catch you before you fall. There will also be padded guardrails on either side of you, so that you can regain your balance. In the event that you do loose balance, there is a minor risk of discomfort or bruising resulting from being 'caught' by the harness. There is also a minor risk of abrasion or bruising if you should contact the guardrails violently.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation. Under Commonwealth of Virginia law, workers compensation does not apply to volunteers. Appropriate health insurance is strongly recommended to cover these types of expenses.

This research project will help understand a potential cause of construction worker falls, and help to minimize the occurrence of falls related to joist buckling. While this research may yield such benefits, no promise or guarantee of benefits will be made to you as a participant. Participants may contact the investigators listed at the end of Consent Form to inquire about the results and conclusions of this research.

IV. Extent of Anonymity and Confidentiality

Your personal information and identity will be kept in the strictest of confidence. No names will appear on questionnaires or surveys, and a coding system will be used to associate your identity with questionnaire answers and data. The list associating names with answers will be destroyed one month after completion of data collection. All information will be collected in a file and locked when not being used, and only the investigators have access to the data. It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

V. Informed Consent

You will receive two informed consent forms to be signed before beginning the experiment; one for your record and one for the experimenter's record.

VI. Compensation

You will be compensated for your participation at a rate of $10 per hour. You will be paid at the end of this study in cash.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty. There may be circumstances under which the investigator may determine that the experiment should not be continued. In this case, you will be compensated for the portion of the project completed.

VIII. Approval of Research
The Department of Industrial and Systems Engineering has approved this research, as well as the Institutional Review Board (IRB) for Research Involving Human Participants at Virginia Tech.

IX. Participant's Acknowledgments

Check in the box if the statement is true:

- ☐ I have U.S citizenship.
- ☐ I am not under the influence of alcohol or drugs.
- ☐ I have no current or recent (past year) musculoskeletal problems (the experimenter will discuss this with you).

X. Participant's Responsibilities
I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand the aforementioned instructions
2. To answer questions, surveys, etc. honestly and to the best of my ability
3. Be aware that I am free to ask questions at any point time

XI. Participant's Permission
I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the responsibilities noted above, to the best of my ability, or to inform the investigators if I am unable to comply with these.

____

Participant's Signature   Date

____

Experimenter's Signature   Date

Signature Page

I have read the description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate with the understanding that I may discontinue participation at any time if I choose to do so.

____

Participant's Signature Date

____

Printed Name

The research team for this experiment is led by Drs Hindman and Nussbaum. They may be contacted at the following addresses and phone numbers:

Dr. Daniel P. Hindman
Assistant Professor
Department of Wood Science & Forest Products
1650 Ramble Road
Blacksburg, VA 24061
(540) 231-9442

Dr. Maury A. Nussbaum
Associate Professor
Department of Industrial and Systems Engineering
250 Durham Hall
Blacksburg, VA 24061
(540) 231-6053

In addition, if you have any detailed questions regarding your rights as participant in University Research, you may contact the following individual:

Dr. David Moore
Chair, Virginia Tech Institutional Review Board
for the Protection of Human Subjects
Office of Research Compliance
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24061
(540) 231-4991

Appendix C– Questionaire for the 60 in. Brace Configuration

Test Specimen Number: ____________________ Age: ____________________________

Weight: _________________________________ Sex: ____________________________

Height: _________________________________ Racial / Ethnic Group: ______________

Occupation: _____________________________

Set Up A

At what point on the I-joist was walking the most difficult?

At the bracing points

Middle of the bracing points

There was no difference along the beam

Other:

____

What do you think made walking more difficult?

Set Up B

At what point on the I-joist was walking the most difficult?

At the bracing points

Middle of the bracing points

There was no difference along the beam

Other:

____

What do you think made walking more difficult?

Set Up C

At what point on the I-joist was walking the most difficult?

At the bracing points

Middle of the bracing points

There was no difference along the beam

Other:

____

What do you think made walking more difficult?

Set Up D

At what point on the I-joist was walking the most difficult?

At the bracing points

Middle of the bracing points

There was no difference along the beam
Other:
____
What do you think made walking more difficult?

Set Up E

At what point on the I-joist was walking the most difficult?

At the bracing points
Middle of the bracing points
There was no difference along the beam
Other:
____
What do you think made walking more difficult?

Final Questions and Comments

At what point did you feel comfortable walking?

Do you feel the walking speed was too fast to keep your balance?

How much did the bracing help with ease of walking? (1 = none at and 5 = made it easy)

Any additional comments?

Appendix D – Questionaire for the 80 in. Brace Configuration

Test Specimen Number: ____________________ Age: ______________________________
Weight: ___________________________________ Sex: ______________________________
Height: ___________________________________ Racial / Ethnic Group: ______________
Occupation: ______________________________

Set Up F

At what point on the I-joist was walking the most difficult?

At the bracing points
Middle of the bracing points
There was no difference along the beam
Other:

____

What do you think made walking more difficult?

Set Up G

At what point on the I-joist was walking the most difficult?

At the bracing points
Middle of the bracing points
There was no difference along the beam
Other:

____

What do you think made walking more difficult?

Set Up H

At what point on the I-joist was walking the most difficult?

At the bracing points
Middle of the bracing points
There was no difference along the beam
Other:

____

What do you think made walking more difficult?

Set Up I

At what point on the I-joist was walking the most difficult?

At the bracing points

Middle of the bracing points
There was no difference along the beam
Other:

What do you think made walking more difficult?

Set Up J

At what point on the I-joist was walking the most difficult?

At the bracing points
Middle of the bracing points
There was no difference along the beam
Other:

What do you think made walking more difficult?

Final Questions and Comments

At what point did you feel comfortable walking?

Do you feel the walking speed was too fast to keep your balance?

How much did the bracing help with ease of walking? (1 = none at and 5 = made it easy)

Any additional comments?

Appendix E – Test Subjects' Physical Properties

60 in. Brace Configuration

Specimen #	Age	Sex	Ethnicity	Occupation	Weight (lb)	Height (in)	W / H (lb/in)
1	23	M	Mid-East	Student	178.2	74	2.408
2	23	M	Caucasian	Student	203.1	72	2.821
3	24	M	Caucasian	Student	218.0	69	3.159
4	23	M	Caucasian	Student	213.2	77	2.769
5	30	M	Asian	Student	220.0	70	3.143
6	29	M	Caucasian	Framer	153.0	72.5	2.110
7	32	M	Caucasian	Contractor	194.0	71	2.732
8	27	M	Caucasian	Builder	183.6	69	2.661
9	24	M	Caucasian	Student	180.0	72	2.500
10	23	M	Caucasian	Student	160.4	73	2.197

80 in. Brace Configuration

Specimen #	Age	Sex	Race	Occupation	Weight (lb)	Height (in)	W / H (lb/in)
21	24	M	Caucasian	student	180.0	72	2.500
22	24	M	Caucasian	student	217.5	69	3.152
23	24	M	Caucasian	student	209.2	74	2.827
24	23	M	Caucasian	student	203.4	72	2.825
25	23	M	Mid-East	student	177.0	74	2.392
26	22	M	Caucasian	student	161.0	70	2.300
27	23	M	Caucasian	student	216.2	77	2.808
28	31	M	Caucasian	framer	165.0	67	2.463
29	23	M	Caucasian	framer	135.0	68	1.985
30	36	M	Caucasian	carpenter	200.0	71	2.817

Appendix F – Raw Data for the 60 in. Brace Configuration

Test Setup A

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
1	0.125	4.275	0.615	1.389
	0.250	3.488	1.181	2.518
	0.375	6.002	1.466	4.230
	0.500	5.072	1.600	4.836
2	0.125	9.322	0.618	1.478
	0.250	7.595	1.178	2.647
	0.375	9.676	1.348	3.702
	0.500	8.473	1.415	3.777
3	0.125	2.480	0.655	1.343
	0.250	2.632	1.268	2.384
	0.375	3.383	1.539	4.416
	0.500	2.815	1.654	5.042
4	0.125	4.445	0.841	1.933
	0.250	2.664	1.621	3.395
	0.375	3.484	1.842	4.753
	0.500	3.483	1.983	5.084
5	0.125	6.662	0.774	1.524
	0.250	4.179	1.466	2.940
	0.375	6.069	1.781	4.242
	0.500	5.908	1.950	4.680
6	0.125	4.611	0.512	0.922
	0.250	3.494	0.968	1.538
	0.375	5.980	1.203	3.973
	0.500	4.705	1.390	4.267
7	0.125	6.996	0.673	1.207
	0.250	4.140	1.266	2.148
	0.375	7.418	1.600	4.483
	0.500	7.714	1.851	5.155
8	0.125	4.988	0.705	1.319
	0.250	4.676	1.334	2.376
	0.375	6.266	1.669	4.631
	0.500	6.288	1.955	5.538
9	0.125	7.570	0.922	1.826
	0.250	5.839	1.746	3.176
	0.375	9.999	2.069	6.008

	0.500	9.480	2.443	7.055
10	0.125	6.484	0.538	1.349
	0.250	3.550	1.024	2.362
	0.375	7.256	1.213	4.135
	0.500	4.352	1.417	4.769

Test Setup B

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
1	0.125	14.775	0.473	1.118
	0.250	10.771	0.872	1.811
	0.375	18.040	1.149	3.830
	0.500	23.671	1.230	4.284
2	0.125	15.523	0.379	0.931
	0.250	10.017	0.690	1.851
	0.375	19.644	0.936	3.158
	0.500	17.379	1.049	3.456
3	0.125	21.527	0.457	0.921
	0.250	14.020	0.888	1.705
	0.375	24.778	1.093	3.065
	0.500	26.811	1.197	3.296
4	0.125	18.024	0.399	0.882
	0.250	12.062	0.749	1.561
	0.375	18.842	0.950	3.042
	0.500	22.375	1.049	3.489
5	0.125	10.216	0.458	1.084
	0.250	6.575	0.884	2.085
	0.375	12.413	1.127	3.225
	0.500	11.690	1.266	3.626
6	0.125	2.458	0.287	0.832
	0.250	1.905	0.539	1.370
	0.375	2.627	0.653	2.166
	0.500	2.171	0.741	2.516
7	0.125	4.668	0.358	0.699
	0.250	3.194	0.657	1.366
	0.375	5.523	0.788	2.705
	0.500	5.626	0.934	3.198
8	0.125	12.169	0.482	0.908
	0.250	8.353	0.898	1.529
	0.375	19.232	1.138	4.072

	0.500	14.428	1.318	4.719
9	0.125	7.871	0.527	1.145
	0.250	5.245	1.025	1.767
	0.375	8.186	1.346	4.488
	0.500	7.085	1.541	5.024
10	0.125	6.658	0.430	1.069
	0.250	4.528	0.787	1.842
	0.375	7.588	0.981	3.347
	0.500	5.158	1.158	3.868

Test Setup C

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
1	0.125	4.122	0.450	1.072
	0.250	4.564	0.833	1.581
	0.375	6.003	1.036	3.472
	0.500	4.925	1.141	3.897
2	0.125	10.395	0.230	0.655
	0.250	5.397	0.419	1.253
	0.375	10.059	0.541	2.306
	0.500	7.040	0.601	2.514
3	0.125	3.207	0.404	1.050
	0.250	3.163	0.758	2.206
	0.375	3.787	1.022	3.302
	0.500	4.194	1.145	3.800
4	0.125	3.390	0.412	0.870
	0.250	4.161	0.767	1.598
	0.375	5.611	0.982	3.459
	0.500	5.228	1.053	3.778
5	0.125	9.619	0.285	0.870
	0.250	7.295	0.545	1.440
	0.375	8.537	0.697	2.461
	0.500	6.243	0.772	2.693
6	0.125	3.106	0.206	0.472
	0.250	2.035	0.383	0.767
	0.375	2.562	0.535	1.917
	0.500	2.731	0.613	2.168
7	0.125	2.133	0.270	0.658
	0.250	2.222	0.469	1.017
	0.375	2.763	0.692	2.759

	0.500	2.536	0.812	3.291
8	0.125	6.570	0.249	0.726
	0.250	3.074	0.474	1.258
	0.375	5.041	0.598	2.243
	0.500	3.689	0.723	2.699
9	0.125	8.279	0.313	0.690
	0.250	3.675	0.576	1.364
	0.375	7.993	0.732	2.809
	0.500	4.927	0.866	3.041
10	0.125	2.947	0.251	0.736
	0.250	2.761	0.439	1.200
	0.375	2.963	0.563	1.999
	0.500	4.076	0.649	2.322

Test Setup D

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
1	0.125	4.339	0.344	0.709
	0.250	3.719	0.627	1.144
	0.375	6.305	0.864	3.303
	0.500	6.380	0.895	3.628
2	0.125	4.952	0.213	0.584
	0.250	4.870	0.404	1.132
	0.375	6.547	0.566	2.082
	0.500	4.785	0.608	2.262
3	0.125	2.684	0.306	0.723
	0.250	2.309	0.583	1.346
	0.375	3.322	0.767	2.679
	0.500	2.863	0.835	2.989
4	0.125	2.741	0.431	1.057
	0.250	2.869	0.800	1.881
	0.375	4.298	1.009	3.653
	0.500	3.772	1.013	3.720
5	0.125	12.982	0.402	0.918
	0.250	9.421	0.747	1.655
	0.375	13.694	0.858	2.454
	0.500	8.934	0.854	2.591
6	0.125	2.057	0.150	0.376
	0.250	2.878	0.286	0.885
	0.375	2.267	0.375	1.438

	0.500	1.941	0.437	1.700
7	0.125	1.398	0.178	0.620
	0.250	1.296	0.361	0.992
	0.375	2.002	0.437	1.668
	0.500	1.321	0.534	1.920
8	0.125	2.581	0.243	0.545
	0.250	1.948	0.479	1.204
	0.375	4.259	0.649	2.389
	0.500	2.625	0.799	2.839
9	0.125	4.273	0.295	0.738
	0.250	3.682	0.556	1.187
	0.375	6.439	0.702	2.746
	0.500	5.810	0.796	3.389
10	0.125	2.076	0.190	0.510
	0.250	2.011	0.345	0.839
	0.375	2.292	0.438	1.717
	0.500	1.424	0.543	2.185

Test Setup E

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
1	0.125	7.808	0.370	0.554
	0.250	4.015	0.638	0.782
	0.375	5.948	0.870	3.145
	0.500	3.398	0.917	3.545
2	0.125	7.076	0.120	0.412
	0.250	3.406	0.208	0.615
	0.375	7.398	0.292	1.308
	0.500	3.139	0.296	1.350
3	0.125	2.027	0.216	0.352
	0.250	1.635	0.381	0.625
	0.375	2.453	0.512	1.960
	0.500	1.358	0.537	1.992
4	0.125	10.192	0.210	0.396
	0.250	4.019	0.357	0.562
	0.375	9.502	0.484	1.737
	0.500	4.242	0.531	1.887
5	0.125	8.858	0.283	0.550
	0.250	3.177	0.508	0.757
	0.375	7.234	0.676	2.727

	0.500	2.544	0.719	2.544
6	0.125	1.771	0.067	0.357
	0.250	0.939	0.093	0.354
	0.375	1.444	0.122	0.543
	0.500	1.544	0.140	0.616
7	0.125	1.797	0.157	0.529
	0.250	1.425	0.258	0.663
	0.375	2.659	0.355	1.493
	0.500	1.341	0.375	1.499
8	0.125	2.818	0.121	0.474
	0.250	1.152	0.197	0.706
	0.375	2.520	0.261	1.120
	0.500	1.534	0.291	1.286
9	0.125	6.597	0.168	0.368
	0.250	2.161	0.271	0.622
	0.375	3.147	0.373	1.582
	0.500	1.928	0.412	1.751
10	0.125	3.059	0.084	0.353
	0.250	0.982	0.149	0.455
	0.375	1.797	0.202	0.878
	0.500	0.757	0.223	1.033

Appendix G – Raw Data for the 80 in. Brace Configuration

Test Setup F

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
21	0.167	3.147	0.678	1.273
	0.333	3.819	1.241	3.538
	0.500	4.122	1.472	4.164
22	0.167	2.396	0.946	1.650
	0.333	3.254	1.733	4.145
	0.500	4.348	2.038	4.891
23	0.167	6.026	0.902	1.696
	0.333	7.618	1.590	5.210
	0.500	6.192	1.819	5.395
24	0.167	8.439	0.706	1.313
	0.333	7.242	1.255	4.214
	0.500	12.077	1.461	5.160
25	0.167	11.400	0.693	1.326
	0.333	8.389	1.196	3.125
	0.500	9.745	1.407	3.736
26	0.167	6.567	0.700	1.184
	0.333	8.238	1.321	5.073
	0.500	9.609	1.456	5.743
27	0.167	2.878	0.610	1.357
	0.333	4.390	1.093	2.831
	0.500	4.897	1.238	3.264
28	0.167	N/A	0.742	1.140
	0.333	5.700	1.277	4.537
	0.500	7.870	1.601	5.345
29	0.167	N/A	0.984	1.796
	0.333	11.087	1.530	4.962
	0.500	12.042	1.759	6.068
30	0.167	N/A	1.372	2.175
	0.333	6.759	2.291	6.690
	0.500	9.847	2.708	10.692

Test Setup G

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)

21	0.167	4.563	0.512	1.029
	0.333	4.483	0.887	2.716
	0.500	7.658	0.974	2.975
22	0.167	2.176	0.570	1.118
	0.333	3.134	1.054	2.955
	0.500	2.500	1.187	3.253
23	0.167	5.079	0.814	1.467
	0.333	7.692	1.351	4.247
	0.500	6.766	1.460	4.626
24	0.167	6.977	0.718	1.551
	0.333	7.249	1.216	3.725
	0.500	9.225	1.425	4.473
25	0.167	8.961	0.795	1.283
	0.333	13.698	1.507	4.703
	0.500	7.582	1.706	5.303
26	0.167	5.248	0.581	1.211
	0.333	7.520	1.031	3.758
	0.500	6.837	1.165	4.156
27	0.167	2.879	0.481	0.969
	0.333	3.407	0.825	2.514
	0.500	4.962	0.947	2.960
28	0.167	N/A	0.463	1.009
	0.333	4.784	0.797	2.405
	0.500	4.832	0.874	2.543
29	0.167	N/A	0.599	1.066
	0.333	7.550	0.982	3.221
	0.500	8.225	1.136	3.885
30	0.167	N/A	0.764	1.315
	0.333	12.192	1.306	4.137
	0.500	18.803	1.511	5.110

Test Setup H

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
21	0.167	4.296	0.400	1.152
	0.333	6.662	0.664	2.667
	0.500	8.542	0.770	2.887
22	0.167	2.771	0.463	1.084
	0.333	3.537	0.832	2.748
	0.500	3.859	0.923	2.993

23	0.167	3.033	0.466	0.873
	0.333	4.105	0.906	3.004
	0.500	4.139	0.954	3.256
24	0.167	4.171	0.405	1.031
	0.333	5.490	0.755	2.823
	0.500	6.050	0.884	3.248
25	0.167	4.826	0.471	0.969
	0.333	4.624	0.815	2.808
	0.500	4.915	0.952	3.232
26	0.167	4.240	0.269	0.464
	0.333	5.990	0.566	2.439
	0.500	7.219	0.659	2.942
27	0.167	2.848	0.422	1.297
	0.333	3.440	0.800	2.600
	0.500	3.443	0.859	2.900
28	0.167	N/A	0.506	1.106
	0.333	4.422	0.895	3.016
	0.500	7.391	0.985	3.454
29	0.167	N/A	0.247	0.522
	0.333	2.442	0.409	1.509
	0.500	3.456	0.465	1.728
30	0.167	N/A	0.375	0.988
	0.333	3.734	0.651	2.286
	0.500	4.561	0.805	2.928

Test Setup I

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
21	0.167	4.779	0.340	1.058
	0.333	5.778	0.623	2.338
	0.500	9.606	0.694	2.755
22	0.167	2.652	0.339	1.207
	0.333	3.684	0.643	2.235
	0.500	2.839	0.755	2.721
23	0.167	3.383	0.370	0.828
	0.333	4.064	0.687	2.737
	0.500	4.458	0.820	3.247
24	0.167	4.426	0.267	0.612
	0.333	4.989	0.523	1.830
	0.500	5.992	0.576	2.067

25	0.167	4.038	0.325	0.795
	0.333	4.071	0.589	2.171
	0.500	6.716	0.649	2.382
26	0.167	2.324	0.304	0.586
	0.333	3.300	0.555	2.218
	0.500	5.041	0.633	2.375
27	0.167	5.249	0.419	1.017
	0.333	4.946	0.791	2.821
	0.500	6.732	0.801	2.891
28	0.167	N/A	0.291	0.825
	0.333	3.430	0.528	2.207
	0.500	5.148	0.630	2.405
29	0.167	N/A	0.178	0.561
	0.333	2.238	0.310	1.153
	0.500	2.353	0.378	1.246
30	0.167	N/A	0.425	0.713
	0.333	3.944	0.819	3.253
	0.500	5.821	0.987	4.047

Test Setup J

Test Subject	Position (x/L)	Lateral Accelerations (m/s^2)	Lateral Displacements (in)	Twists (deg)
21	0.167	6.590	0.182	0.464
	0.333	2.320	0.327	1.421
	0.500	3.787	0.394	1.526
22	0.167	2.959	0.292	0.728
	0.333	2.752	0.568	2.323
	0.500	3.176	0.660	2.531
23	0.167	3.522	0.257	0.674
	0.333	2.891	0.460	2.042
	0.500	6.020	0.547	2.472
24	0.167	6.235	0.219	0.627
	0.333	3.347	0.370	1.524
	0.500	8.792	0.443	1.627
25	0.167	3.297	0.260	0.581
	0.333	3.727	0.518	2.202
	0.500	4.566	0.586	2.506
26	0.167	2.486	0.193	0.356
	0.333	2.471	0.333	1.575
	0.500	2.718	0.377	1.659
27	0.167	1.965	0.182	0.568
	0.333	2.736	0.331	1.513

	0.500	2.052	0.403	1.574
28	0.167	N/A	0.288	0.612
	0.333	3.154	0.502	1.651
	0.500	4.726	0.573	1.997
29	0.167	N/A	0.187	0.649
	0.333	1.754	0.302	1.191
	0.500	2.136	0.358	1.458
30	0.167	N/A	0.158	0.565
	0.333	3.825	0.301	1.147
	0.500	2.641	0.348	1.341