# Lateral Buckling

## Recent Research on the Testing and Installation of Unbraced I-joists During Construction

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The construction industry has seen a large growth in the use of wood composite products during the last 20 years. Many of these composites have demonstrated equivalent or greater design properties compared to solid-sawn wood.

Wood composites also represent a more efficient use of wood fiber during manufacturing. In particular, wood composite I-joists represent a very efficient use of wood material using a shape that maximizes the bending stiffness while minimizing the material used.

Though wood composites and solid-sawn lumber originate from the same source, there are subtle and important differences between these products. The alignment of wood strands or fibers in a composite can increase the design properties of wood composites in a specified direction, but often lowers the design properties in other directions.

One example where the properties of wood composites differ from solid-sawn lumber is lateral buckling. Lateral buckling, or twisting out, is a condition where an unbraced joist may twist and deflect laterally from a vertically applied load.

Lateral buckling only occurs when a joist is unbraced, such as during construction. The attachment of purlins or sheathing on the top edge of the joist prevents lateral buckling caused by gravity loads. The instability of lateral buckling may cause a joist to fail or cause the load (construction workers or construction materials) to fall.

Of special concern in the area of lateral buckling are wood composite I-joists. This article will explore the lateral buckling of I-joists, including the current NDS design equations, test conditions used for experimental measurement and the difficulties of measuring the lateral buckling potential of workers walking on unbraced beams. This research represents preliminary work performed at Virginia Tech, which will be explored in more detail.

### Formation of NDS Design Equations for Lateral Buckling

Lateral buckling of wood members has received little attention in the past. The foundation of lateral buckling design for solid-sawn lumber was done by Hooley and Madsen in 1964. This research tested the lateral buckling of glue-laminated beams with a dead load suspended from the center of a simply supported beam.

These results were applied to the wood design methodology using three separate equations for three different kinds of buckling behavior — short beams, which do not buckle; intermediate beams, which experience inelastic buckling defined by an empirical equation; and long beams, which experience elastic buckling as defined by the Euler buckling equation.

In the 1991 revision of the NDS, these three equations were incorporated into a single equation, known as the Ylinen equation, for computational ease. The Ylinen equation is a smoothed curve that corresponds very well with the results from the three previous equations.

Accounting for lateral buckling of wood members during design is accomplished by multiplying the reference bending design value by a beam stability factor, $C_L$. The National Design Specification for Wood developed the $C_L$ factor as a function of the Ylinen equation, which includes the beam slenderness ratio ($R_B$), the reference allowable bending stress if the beam was fully braced ($F_B$*) and the critical buckling

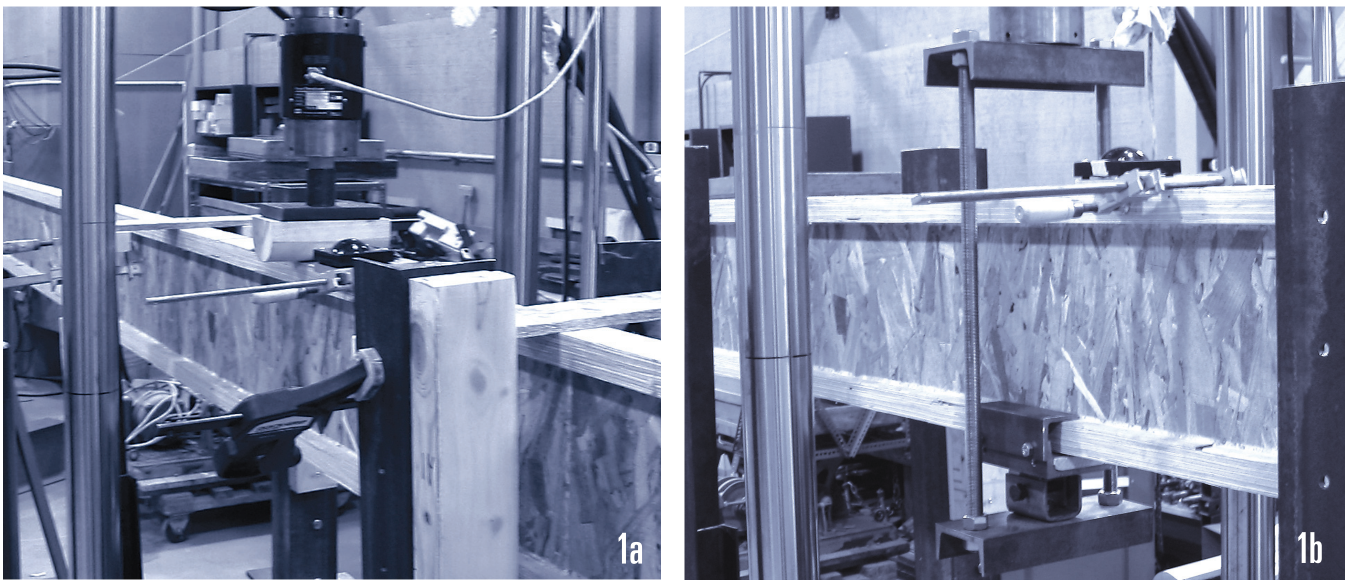


Figure 1: Different Loading Conditions for Unbraced I-joist Testing, (1a) Top Flange Loading, (1b) Bottom Flange Loading

design value for bending members ($F_{bE}$). The slenderness ratio is a function of the specimen height, unbraced length, and includes the boundary conditions of beam end support. The unbraced length is the maximum distance between end or intermediate supports that provide alignment to the compression edge of the joist. The critical buckling design value for bending members is based upon the Euler bending stress and represents a theoretical buckling limit stress, which includes a safety factor for the variation of material. These equations are further detailed in the Section "NDS Lateral Stability Adjustment Factor."

The Euler bending stress is a combination of the off-axis bending stiffness ($EI_y$) and the torsional rigidity (GJ) of the cross-section. The NDS equations include a series of simplifying assumptions including the use of a rectangular, homogenous cross-section and a predetermined ratio of the elastic modulus to shear modulus.

Wood composite I-joist design values published by manufacturers represent the completely braced situation where lateral buckling would not occur ($C_L$ = 1.0). The NDS also provides recommendations for the calculation of the beam stability factor, $C_L$. Since the I-joist is not a rectangular section, the CL term is replaced by the column stability factor, $C_P$, considering the compression flange as a column with an unbraced length and end supports identical to the I-joist conditions.

Recommendations by I-joist manufacturers clearly state I-joists should not be used in an unbraced condition. Also, the manufacturers state care should be taken during construction to keep workers off of unbraced I-joists until strapping or sheathing has been installed. However, there is no recommendation on how workers are supposed to attach sheathing or strapping. Workers sometimes choose to walk on unbraced I-joists to speed their installation — a major concern since safety harnesses are seldom employed on residential sites for fall protection during installation of floor and roof decks.

Recent interest has sparked research into the lateral stability of wood composite materials. Work performed by Hindman et al. (2006a and 2006b) measured the lateral buckling loads of solid-sawn MSR lumber, structural composite lumber (LVL, PSL, LSL) and wood composite I-joists. The solid-sawn lumber and SCL results showed good agreement with the NDS equations, while the I-joist results were severely under-predicted by the current LRFD equations. Burow et al. (2006) demonstrated the use of the moment magnification factor from steel design to be useful in predicting the buckling loads of I-joists. The use of longer span I-joists for roof and floor applications has brought into question

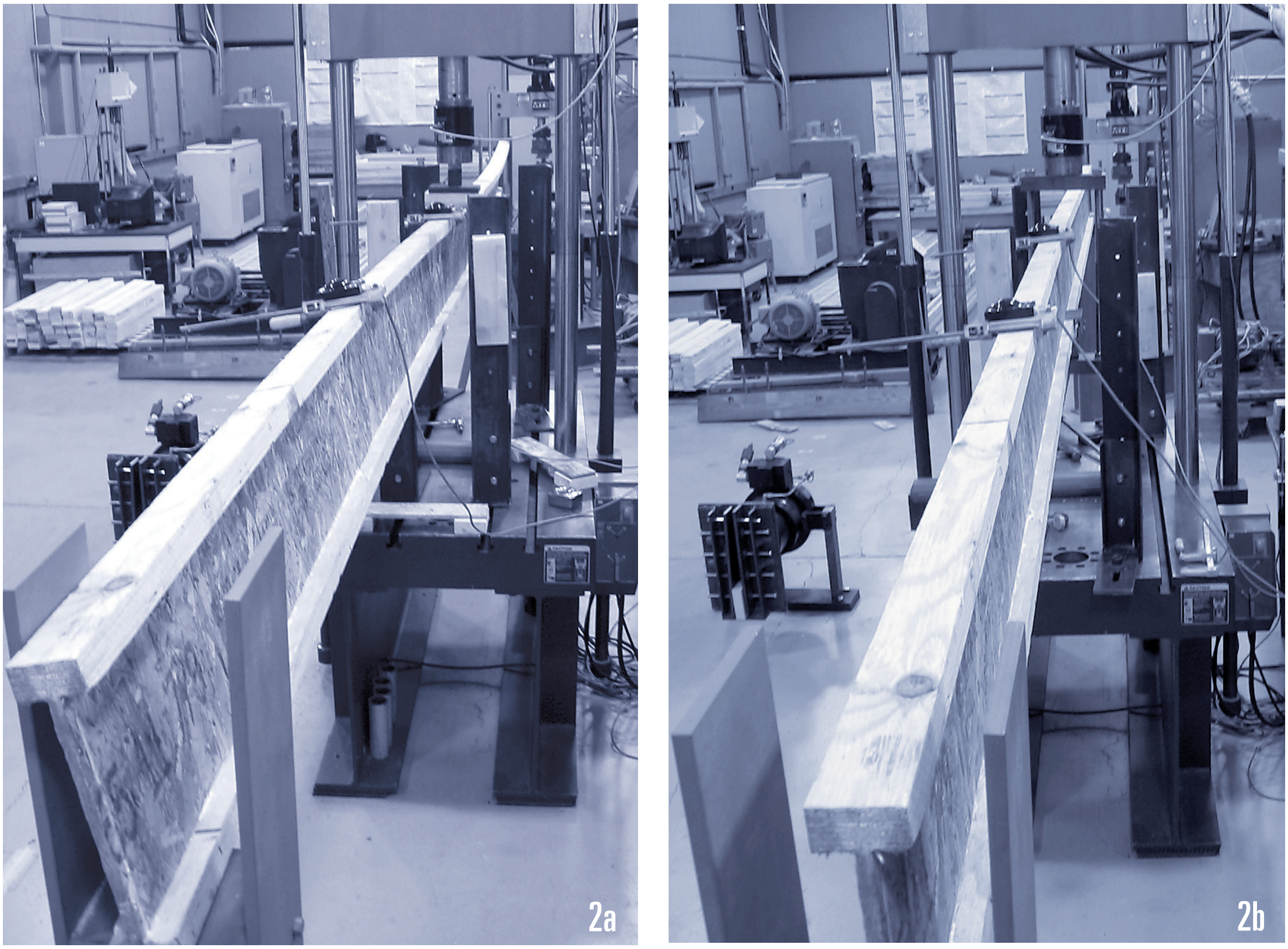


Figure 2: Final Buckled Shape of I-joist from Testing, (2a) Top Loading Condition, (2b) Bottom Loading Condition

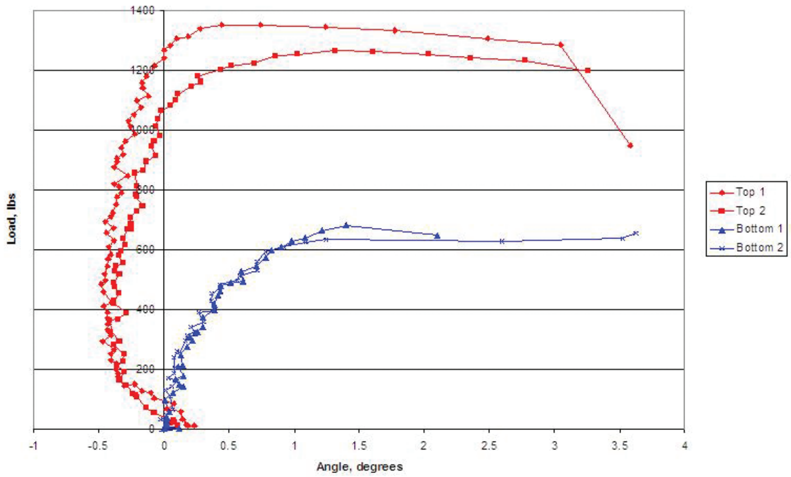


**Figure 3: Graph of Load vs. Angle Comparing Top Loading and Bottom Loading Testing**

whether the loads caused by a worker on an I-joist can cause buckling to occur.

## Testing of a Single, Unbraced I-joist

The testing of lateral buckling of a single unbraced I-joist is rather difficult. Previous researchers have used an upward force or a dead load poured into a container suspended from the specimen. This testing requires specialized equipment, and data collection over the range of buckling behavior may be difficult to measure. The use of a universal testing machine would be favorable for ease of testing and data collection. However, using a vertically applied load from a universal testing machine can create a point of lateral support where the load head contacts the top, or compression, flange of the I-joist. By creating a point of lateral support, the unbraced length of the beam is halved, severely limiting the range of unbraced lengths that can be analyzed. Figure 1a shows the test configuration using a "top flange loading" position for an unbraced I-joist.

One possible strategy to prevent a point of lateral support being formed at the load point is to use a loading jig, which applies the load to the bottom flange of the I-joist. This loading jig is shown in Figure 1b, noted at the "bottom flange loading." A hinge was incorporated below the bottom flange to allow rotation of the joist to occur while still allowing the load to be transferred to the specimen. This loading jig eliminates the bracing of the load head described above and allows a larger range of unbraced lengths to be tested.

The two loading jigs were tested with an 11-7/8-inch high I-joist with simple supports on a 20-foot long span to examine the difference in buckling behavior. Figure 2 shows the buckled shapes of the I-joists. For the top loading condition (Figure 2a), the I-joist shows an S-shape curve with the load point remaining in line with the support points. The bottom loading condition (Figure 2b) shows the I-joist in a U-shape, with the loading point of the I-joist showing significant rotation and lateral deflection. Therefore, the bottom-loading jig provides a better representation of a load that does not provide bracing placed on top of an I-joist.

Testing of the I-joists included measurement of the applied load and measurement of the angle of the top flange at multiple points along the length of the beam. Figure 3 shows the load-angle plot for the testing of the top loading and bottom loading jigs. The maximum load of the top loading condition was greater than the bottom loading condition due to the reduction in unbraced length caused by the point of lateral support formed by the top-loading jig.

The shape of the load-angle curve also shows some differences between the top and bottom loading conditions. For the top loading, the I-joist maintained a vertical position (with some sway between -0.5 and 0.5 degrees) until the buckling load was attained. This is considered the classic case of elastic buckling, where a distinct bifurcation is observed. Bifurcation is defined as a distinct point on the load-angle graph where the load is constant, but the angle increases rapidly. The bottom loading condition showed a gradual change in angle as load increased, finally reaching the buckling load at an angle of 1.5 degrees. When a load is applied to the I-joist away from a point of lateral support, there is not really a bifurcation of the load, but more a gradual change in the angle of the I-joist.

## Effect of I-joist Size on Buckling Load

Figure 4 shows the load-angle curves from the testing of three different I-joist heights using the bottom-loading jig

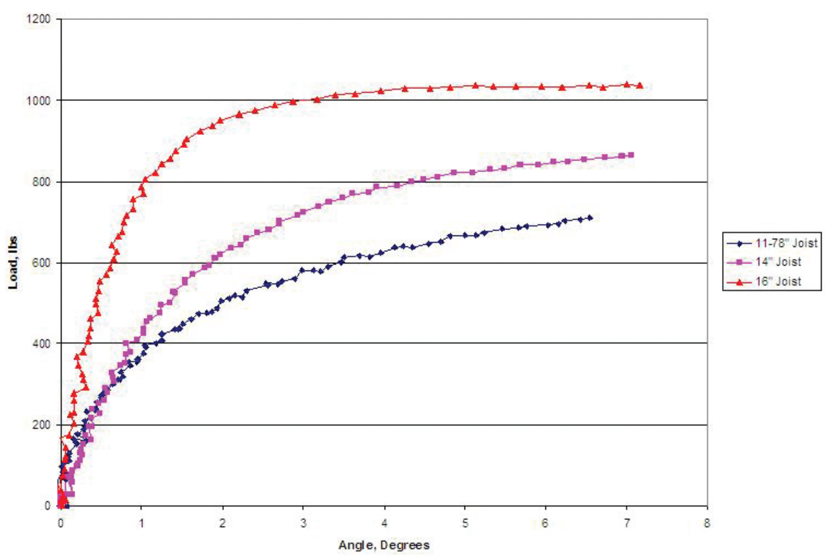


**Figure 4: Load-Angle Curves for I-joists of Different Heights** (All Joist Top Flanges 2-3/8" Wide)

described above. The three I-joist sizes are 11-7/8 inches, 14 inches and 16 inches tall. The 11-7/8-inch tall I-joist is the most popular size used in residential construction, but all three sizes are commercially available. All of these I-joists had a flange width of 2-3/8 inches. The I-joists were tested at a 20-foot long span with simple supports. As the height of the I-joist increased, so did the buckling load. The 16-inch tall I-joist load-angle curve shows a bifurcated load ó where a maximum load of 1,033 pounds was reached and then the load held steady as the angle continues to increase. The load-angle curves of the 14-inch and 11-7/8-inch tall I-joists did not reach bifurcation, with both load and angle continuing to increase, albeit at a decreasing rate.

## Determination of Buckling Load

Figure 4 demonstrates some of the results observed for I-joists using the bottom-loading jig. One question that has not been adequately defined for the study of lateral buckling is which load should be chosen as the buckling load. Several different criteria exist for this, which may or may not be adequate to explain what is happening. First, the definition of buckling from mechanics includes a distinct bifurcation, where load remains constant while the angle of rotation increases. Some definitions of falls include an event where the center of mass moves outside of the base of support. Given this definition, a maximum angle of rotation attained, arbitrarily chosen as 1.0 degree, could be used. Burow et al. (2006) used a change in angle of 0.2 degrees between data points. This change in angle represents an acceleration of the I-joist, which also has been shown in some sources to be a cause of falls ó however no limiting values are given.

Table 1 shows a comparison of the buckling loads determined from these three methods. The buckling loads at bifurcation were not applicable for the 11-7/8-inch and 14-inch I-joists, since the buckling loads continued to increase, even after 5 degrees of rotation. The buckling loads at 1.0 degree were the lowest buckling criteria for all three I-joists. The change in angle of 0.2 degrees produced higher buckling loads than the absolute angle, but may not be consistent with work by Burrow et al. since the loading speed and data acquisition rates of the current testing were not equal to previous work.

A review of literature related to falls produces no concrete recommendations as to what angle of surface or change in angle constitutes a fall. The case of a worker standing on a single I-joist is a much more difficult case to understand, since a workerís foot placement would be front to back, rather than a typical side-by-side foot placement. Also, the small size of the I-joist flange inhibits the workerís ability to sense a fall event is happening since the edges of the shoe and foot are not braced against a surface.

To provide a more definite answer to this question, future studies will analyze the loads caused by workers upon I-joists and attempt to characterize if those loads cause lateral buckling to occur. Workers also "joist-hop" by jumping or stepping from one I-joist to another. The action of joist-hop is particularly troubling, since the lateral movement from joist-to-joist induces a torsional moment on the I-joist, thereby lowering the vertical force required to cause lateral buckling. Joist hopping has received no attention in the fall literature.

| I-JOIST HEIGHT | BUCKLING LOAD AT BIFURCATION | BUCKLING LOAD AT 1.0 DEGREES | BUCKLING LOAD AT $\Delta\theta$=0.2 DEGREES |
|---|---|---|---|
| 11 7/8" | N/A | 376 lbs | 545 lbs |
| 14" | N/A | 426 lbs | 715 lbs |
| 16" | 1033 lbs | 770 lbs | 966 lbs |

**TABLE 1.**
**Comparison of Different Methods to Determine Buckling Load from Figure 4**

## Loads Caused by Workers on Unbraced I-Joists

In addition to studying the lateral buckling of I-joists, another part of this research focused on the question of describing the loads that workers impose upon I-joists. While the design of beams for lateral buckling typically focuses on static loading cases, the motion of a worker walking along an I-joist contains a significant dynamic loading component. This dynamic loading component magnifies the static load and can cause a static load greater than the worker's weight due to stepping force.

A safety platform was constructed to allow a person to experience the feeling of lateral buckling without endangering themselves from falling off of a beam. The platform was equipped with hand-rails on either side for participants to maintain balance. In the center of the platform, the unbraced joist is located just above the platform surface with a small opening on either side that does not allow a person's foot to become lodged. Figure 5a shows a student walking on an unbraced I-joist using the safety platform.

For all of the I-joists tested with the safety platform, there was a point near the center where lateral buckling occurred in the form of the I-joist wobbling or, in more severe cases, shaking back and forth. To quantify the load applied to the I-joist, a load cell was placed under the I-joist support at one end. The student walked towards the center and towards the end support with the load cell, so the load measurement increased with each step.

Figure 5b shows a trace of the load caused by the student's steps. The student was instructed to take a step and wait a short period of time for the measurements to take place. The spike in the load represents the dynamic component of the walking stride, which increases the static load by 80 to 100 pounds. Note that as the student moved towards the center, the load measurement started to contain a large amount of noise, or chatter, during the stepping force, or dynamic portion. These spikes were


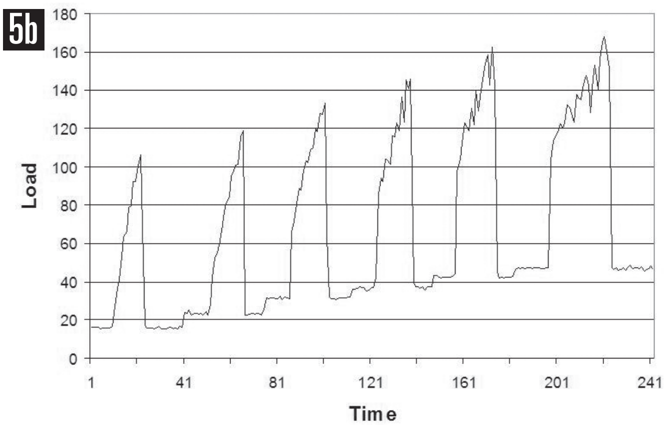


**Figure 5:**
**(5a) Student Walking on Safety Platform,**
**(5b) Load – Time Graph from Safety Platform End Support Load Cell**

concurrent with the I-joist wobbling, which was much more evident when the student stepped than when the student was standing still on the I-joist.

These results are only preliminary, but represent an attempt to quantify the load caused by humans walking on an unbraced I-joist. Future research will also include the loads caused by workers performing tasks such as carrying materials or attaching bracing or sheathing.

## Effect of Bracing on the Buckling Load of An I-joist

Many sources recommend adding bracing to prevent or limit lateral buckling and lower the unbraced length of the beam. To characterize the change in buckling behavior, two braces were placed on the 11-7/8-inch I-joist used for bottom loading jig testing. Braces were 1/2-inch thick OSB attached with a single 8d nail to the top flange of the I-joist. The ends of the OSB were clamped to supports located on either side of the I-joist to prevent movement. Figure 6 shows the position of bracing to the loading jig. Braces were located 2 feet on either side of the load point to allow a long unbraced length on either side of the I-joist (approximately 8 feet).

Figure 7 shows the load-angle curves from testing with and without the bracing installed. The addition of these braces more than doubled the maximum load before buckling occurred. Therefore, if workers do feel a need to walk on unbraced I-joists, the installation of some temporary bracing, even if the bracing is only 1/2-inch thick material, may help to prevent lateral buckling and reduce the tendency for workers to fall.

## Conclusion

This paper provided a review of the lateral buckling criteria used in wood design and discussed recent research on the lateral buckling of unbraced I-joists. The test procedures for measuring the lateral buckling of I-joists are complex and there is no clear method to determine what buckling load should be used for design. Some preliminary work has been conducted to measure the loads caused by humans, which contain a significant dynamic component that can increase the static load by 80 to 100 pounds. Bracing of I-joists was shown to be highly effective in increasing the buckling load. Future work is needed to characterize the lateral buckling loads and the loads caused by humans before relevant conclusions in these areas can be made.

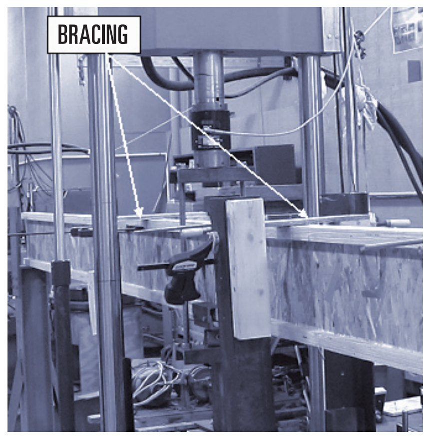


**Figure 6: Location of Bracing for Buckling Load Testing**

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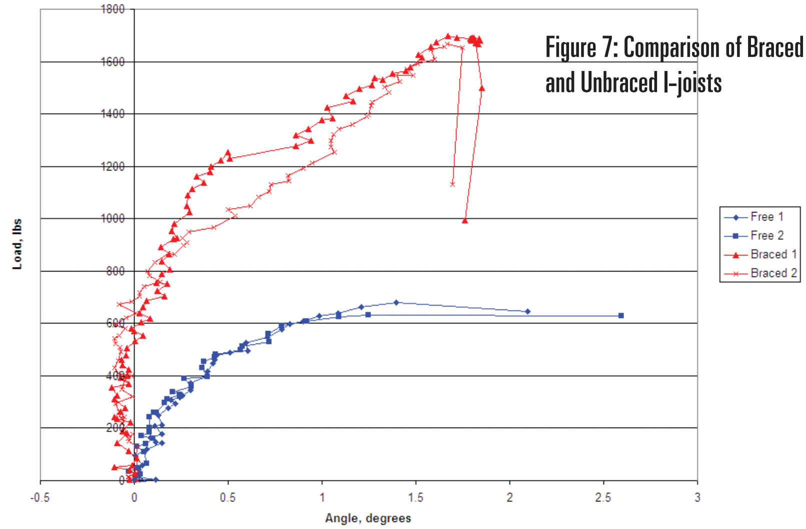

Figure 7: Comparison of Braced and Unbraced I-joists

## NDS Lateral Stability Adjustment Factor

$$F_b' = F_b C_D C_M C_t C_L C_F C_{fu} C_i C_r$$

$$C_L = \frac{1+\left(F_{bE}/F_b^*\right)}{1.9} - \sqrt{\left[\frac{1+\left(F_{bE}/F_b^*\right)}{1.9}\right]^2 - \frac{F_{bE}/F_b^*}{0.95}}$$

$$F_{bE} = \frac{1.20E'_{min}}{R_B^2}$$

$F_b^*$ = bending stress including all other C factors except $C_L$
$R_B$ = slenderness ratio

For I-joists, consider the compression flange of the I-joist as a column.
Calculate $C_P$ of the compression flange and substitute for $C_L$.

$F_C^*$ = compression stress including all factors but $C_P$