Potential Use of Deformed Shank Nails as a Solution to Annoying Vibrations in Wood Floor Systems

Brent Olson
J. Daniel Dolan
Bob Duncan
Henry Schiedermeier

Abstract

In the United States, modern designs of wood floor systems rarely directly account for annoying floor vibration criteria, because it is not a required design criterion in the International Building Code or the International Residential Code. However, adhesives are sometimes used to supplement traditional subfloor fasteners in an effort to improve the floor vibration performance, but they are mainly used to reduce or eliminate homebuilder ''callbacks'' due to floor squeaks. This article addresses using high performance deformed shank fasteners rather than adhesives to minimize common annoying floor vibration problems.

Wood floor systems are designed in the United States under structural and serviceability criteria that pertain to life-safety and to cracking of brittle finishes, respectfully, with limited attention given to vibration design. Current engineered wood systems are designed to span longer lengths with lighter materials, as compared with conventional sawn lumber, and longer spans with lighter materials tend to accentuate vibration issues. The International Building Code (IBC) continues to provide prescriptive span tables for solid sawn lumber floor joists based on design criteria but is silent on vibrations. For engineered wood floor framing members, the IBC (International Code Council [ICC] 2012a) and International Residential Code (IRC; ICC 2012b) simply direct designers to follow manufacturer's specifications for engineered wood products such as I-joists when designing with proprietary products. Other industrial countries' building codes consider vibrations as a serviceability design criterion, including both the National Building Code of Canada (NBCC 2010) and the Eurocodes (European Committee for Standardization [CEN] 2004). Typical floor designs meet safety criteria but many times fail to satisfy owner concerns and serviceability issues caused by annoying vibrations.

Annoying floor vibration is a problem that has been faced by designers, contractors, and owners of buildings for a very long time. Many people can remember when walking across a room could cause vinyl records to skip. Annoying floor vibration can be broken into several categories, such as squeaks, glassware rattling in cabinets, sound transmission, or uncomfortable feelings by people standing or sitting on the floor. This investigation deals only with judging a floor system for comfort when people are standing or sitting on the floor. The criteria used to judge the vibration response of the floor is one that has been used for steel and wood floor systems in the past, and these investigations will be discussed in the following paragraphs. The other classifications of annoying floor vibration are beyond the scope of this testing. Floor serviceability for this manuscript is defined as a state in which floor vibration is limited to an acceptable level, under normal usage, with respect to the comfort of the occupants. Tests on several aspects of human perception of vibration have been conducted by multiple researchers in various fields. Some of the research pertaining to the wood floor vibration is presented below.

The authors are, respectively, Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Washington State Univ., Pullman (bolson19@wsu.edu); Professor and Director of Codes and Standards (jddolan@wsu.edu [corresponding author]) and Research Coordinator (duncanr@wsu.edu), Composite Materials and Engineering Center, Washington State Univ., Pullman; and Engineering Manager, Paslode, an ITW Company, Vernon Hills, Illinois (henry.schiedermeier@paslode.com). This paper was received for publication in December 2013. Article no. 13-00092.

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The possible use of deformed shank nails instead of common nails and adhesive would be beneficial to the builder from a cost perspective by eliminating one material and increasing productivity. The use of the deformed shank nail does not affect the use of finish floor products such as ceramic tile, vinyl, carpet, or floor toppings used for fire and sound control, such as gypcrete and light-weight concrete.

Research to eliminate annoying vibrations has been a focus for many researchers and companies to improve functionality of longer-span designs made possible by engineered wood products. Onysko (1988a) created criteria based on testing, which is used in the NBCC (2010). The deflection criterion is a stiffness-based criterion that considers the deflection owing to a concentrated load at midspan to determine whether a span is acceptable or not. The maximum deflection of 2 mm caused by the concentrated load of 1 kN is what the NBCC uses as a design criterion. The fundamental frequency of joists and girders became a focus in Dolan et al. (1991), Kalkert et al. (1993), Johnson (1994), and Woeste and Dolan (2007). From testing both laboratory and in situ floors, a fundamental frequency less than 15 Hz was found to create annoying vibrations to many evaluators. Acceleration and dynamic impulse velocity were considered useful measures to quantify the annoying vibration response by some researchers.

Several other researchers have investigated floor vibration in an effort to develop criteria for their respective design communities. Onysko (1985, 1988a, 1988b), Chui (1988, 1994), Smith and Chui (1988), Hu (1999), Hu et al. (2001), and Hu and Chui (2004), have developed much of the basis for the design criteria used for residential floor design to minimize annoying vibration in Canada. The research of Ohlsson (1988a, 1988b) formed much of the basis for the design criterion used in the Eurocode 5 design document (CEN 2004).

To solve the annoying vibration problem, designing the system so that the fundamental frequency is maintained above 15 Hz is suggested. For systems where the fundamental frequency criteria cannot be met, Kalkert (1997) suggests imposing doubling stiffness, providing continuous blocking, or incorporating additional subflooring might improve the performance. While adhesives are usually placed between the floor framing and sheathing to eliminate squeaks, they are also considered by some to improve composite action between the floor joists and the subflooring. The intent is to increase the effective structural stiffness, thereby increasing the fundamental frequency of the system above the 15-Hz benchmark. However, Johnson (1994) found that an effective flange width for the sheathing of less than 183 mm (7.25 in.) would negate many of the intended benefits that using adhesives was to provide.

A new option for minimizing floor squeaks has been introduced to the light-frame floor construction marketplace. The product investigated in this experimental study is a deformed shank nail (Paslode TetraGrip subfloor fastener [ESR-30721; ICC Evaluation Service {ICC-ES} 2013]).The data presented in this article were produced by testing and analysis conducted at the Composite Materials and Engineering Center (CMEC) at Washington State University in Pullman, using this proprietary deformed shank nail provided by Paslode and other common materials used for light-frame floor construction. The fastener, TetraGrip (ICC-ES 2013), is a proprietary deformed shank nail and was being presented as an alternative to using supplemental adhesives in wood floor systems to minimize squeaks and reduce annoying vibration problems. The TetraGrip subfloor fastener is threaded almost the entire length of the shank to create composite action between the subflooring and floor joists. While the data referred to in this article pertain to this particular fastener, in general, a deformed shank fastener that grips both the sheathing and framing in a positive manner can improve composite action over smooth shank nails, and this mechanism prevents floor squeaks. The positive mechanism of integral linking of the wood fiber into the deformed shank of the nail provides an active attachment. A smooth shank nail can only hold the sheathing with the head of the nail.

Objective

The objective of this article is to report the findings of an experimental investigation of whether the use of deformed shank nails (TetraGrip subfloor fasteners) to attach floor sheathing provides performance comparable to 8d common nails with elastomeric adhesive with respect to the vibration and strength performance of floors.

Materials and Methods

Vibration and static bending tests were conducted on samples using three different methods of attaching sheathing to floor joists. The tests were conducted to compare the fundamental frequencies and bending stiffness and strength between realistic floor specimens and to determine how effective the different fastening systems are in developing the composite action between the sheathing and floor joists. The tests used double-T specimens, where each specimen consisted of two floor joists sheathed with a common oriented strand board (OSB) sheathing panel. The composite action of double-T floor specimens using I-joist framing and 18-mm (23/32-in.) OSB subflooring with either

1. deformed shank nails, TetraGrip subfloor fastener (60-mm [2 3/8-in.]-long deformed shank),
2. 8d common nails (3.4 by 63.5 mm [0.131 by 2.5 in.]) without adhesive, or
3. 8d common nails with an elastomeric adhesive (Liquid Nails) between the subflooring and the joist.

The joists were spaced at 406 mm (16 in.) on center for all specimens. The deformed shank fastener was tested to compare fundamental frequencies between samples constructed using the TetraGrip subfloor fastener and others using a smooth shank nail with an adhesive, or a smooth shank nail with no adhesive to attach the sheathing to the framing. (For further information on the TetraGrip subfloor fastener, see Duncan et al. 2012a.) Each configuration was tested with five specimens. While the data referred to in this article pertain to this particular fastener, the concept of having deformed shank fasteners is not new to the model codes. While US model codes have recognized deformed shank nails, no increase in withdrawal capacity has been allowed over generic smooth shank nails. The added withdrawal capacity and the resultant composite action is thought to be a key component of the improved performance observed in this testing. The test configuration is shown in Figures 1a and 1b for the testing of the specimens in the unsheathed and sheathed conditions.

A few of the limitations of this testing include the following:

Figure 1.—Floor specimen configurations for testing: (a) unsheathed specimen and (b) sheathed specimen.

1. The assemblies were constructed under dry conditions with dry materials, and they were tested under dry conditions. No moisture cycling to simulate construction wetting was introduced.
2. The specimens represent laboratory-built specimens, and no construction deficiencies, such as nails missing the framing, were included.
3. Vibration complaints frequently occur from single person foot traffic, which is far below the design load levels used.

Two separate I-joist sizes were used to construct the specimens. BCI 90 and BCI 5000, manufactured by Boise Cascade Company (2010), were tested as a double-T floor system, both without and with OSB sheathing. For each I-joist size, spans were chosen to satisfy one of two deflection criteria, L/360 and L/480, for a 27.6-MPa (40-lb/ft^2) distributed live load and a simple span condition. The double-T specimen was used since most residential floor systems are designed and framed to be one-way action ribbed plates, which deform in a similar manner.

Equation 1 is the equation used to calculate the centerline deflection for a distributed load applied to a simply supported joist and was used to determine the spans used for each I-joist size for each deflection criterion as shown in Table 1.

$$\Delta = \frac{5 \times w \times L^4}{384 \times EI} \tag{1}$$

where

Δ = maximum deflection at the midspan of joist meets L/360 or L/480 criteria for simply supported single spans;

w = load per unit length, 780 N/m (4.4 lb/in.) based on 1,915-Pa (40-lb/ft^2) load;

E = modulus of elasticity, MPa (lb/in^2), 1.10×10^6 MPa (160×10^6 lb/in^2) for BCI 5000 and 4.45×10^6 MPa (645×10^6 lb/in^2) for BCI 90; and

I = moment of inertia, mm^4 (in^4).

When quantifying the fundamental frequency, a heel-drop simulation (with the subject weight of 850 N [191 lb]) was used. The process followed was for the individual causing the pulse to rise up on their toes and drop to their heels and hold their position with locked knees. This test is not a standardized test but has been used by previous researchers including Dolan et al. (1991) and Murray et al. (1997). An accelerometer measured the vertical acceleration continuously until the vibration stopped, then the data were processed using DADisp (2012), a signal analysis program.

The data were first passed through a digital band-pass filter to eliminate background noise from the laboratory equipment, passing traffic, and other random sources of vibration. Tests of the laboratory floor indicated that there was a response in the low frequencies (<2 Hz) and high frequencies (40 to 70 Hz), with minor noise in the range of interest. A transition between the zero pass and the full pass regions of the filter was used to avoid reflection issues with the mathematics. This technique is used extensively in signal processing and dynamic testing to remove or isolate frequencies in the raw data and to clarify the data of interest. The band-pass filter was designed to allow or maintain all frequencies between 7 and 30 Hz, while eliminating the frequencies lower than 2 Hz and greater than 35 Hz. The frequencies between 7 and 30 Hz are of interest because humans find vibration between about 8 and 14 Hz to be annoying. The annoyance is due to various organs in the human body having resonant frequencies in this range. This band of frequencies is discussed by many of the research articles discussed in the introduction section of this article. The band-pass filter isolated the response to the range of response of the floor specimens themselves and removed vibrations that were caused by traffic, other equipment in the laboratory, etc.

The filtered data were then passed through a fast Fourier transform (FFT) to determine spectrum of response, which identifies the resonance frequencies that the floor system is responding to when the impact loading of the heel-drop test is applied. The principal peak with the lowest value was selected as representing the fundamental, or natural, frequency of the floor system. The specimens were loaded at the quarter, center, and three-quarter locations of each joist or sheathed specimen to obtain the results. An example of the data analysis is illustrated in Figure 2.

Table 1.—Spans from deflection criteria for 27.6-MPa (40-lb/ft^2) live load.

Joist classification	L/360	L/480
BCI 5000 (m)	5.01	4.55
BCI 5000, in. (ft, in.)	197.3 (16, 5.3)	179.25 (14, 11.25)
BCI 90 (m)	7.975	7.247
BCI 90, in. (ft, in.)	314.0 (26, 2)	285.3 (23, 9.3)

In Figure 2, the top left graph represents the unfiltered acceleration response of the floor system when the heel-drop test was performed. The window to the right is the band-pass filter that was developed using the DADisp filtering module. The top right-hand graph represents the filtered data (the raw data multiplied by the filter). The left-hand graph in the middle row represents the filtered data after a Hanning filter is used to prepare the data for the Spectrum function (FFT; the Hanning filter essentially pads the data with zeros to allow the FFT function to run efficiently, without altering the results). The middle graph shows the spectrum of the filtered data, and the right-hand graph in the middle row shows the spectrum of the raw data. As one can see, the filtered data result in a more defined spectrum of responses when compared with the spectrum of the raw data, which includes all of the background noise as well as the response from the heel-drop loading. Finally, the bottom row of the graph shows the frequencies that have significant power associated with them. The floor fundamental frequency for this specimen is 22.0 Hz; the peak at 20.22 Hz represents the vibration mode of the flexing of the sheathing perpendicular to the joists. The fundamental flexural frequency for the direction of the joist span can be estimated using Equation 2 and the mechanical and section properties of the joists. This equation was first proposed by Murray (1991) and can be used for floors with or without toppings. The fundamental frequency in the direction that the sheathing spans can be estimated using the same equation but using the properties of the sheathing.

$$f = 1.57\sqrt{\frac{g \times EI}{W \times L^3}} \tag{2}$$

where

f = fundamental frequency of joist or girder (Hz),

g = acceleration due to gravity, 9.81 m/s^2 (386 in./s^2),

W = total load supported, 780 N/m (4.4 lb/in.) based on 1,915-Pa (40-lb/ft^2) load,

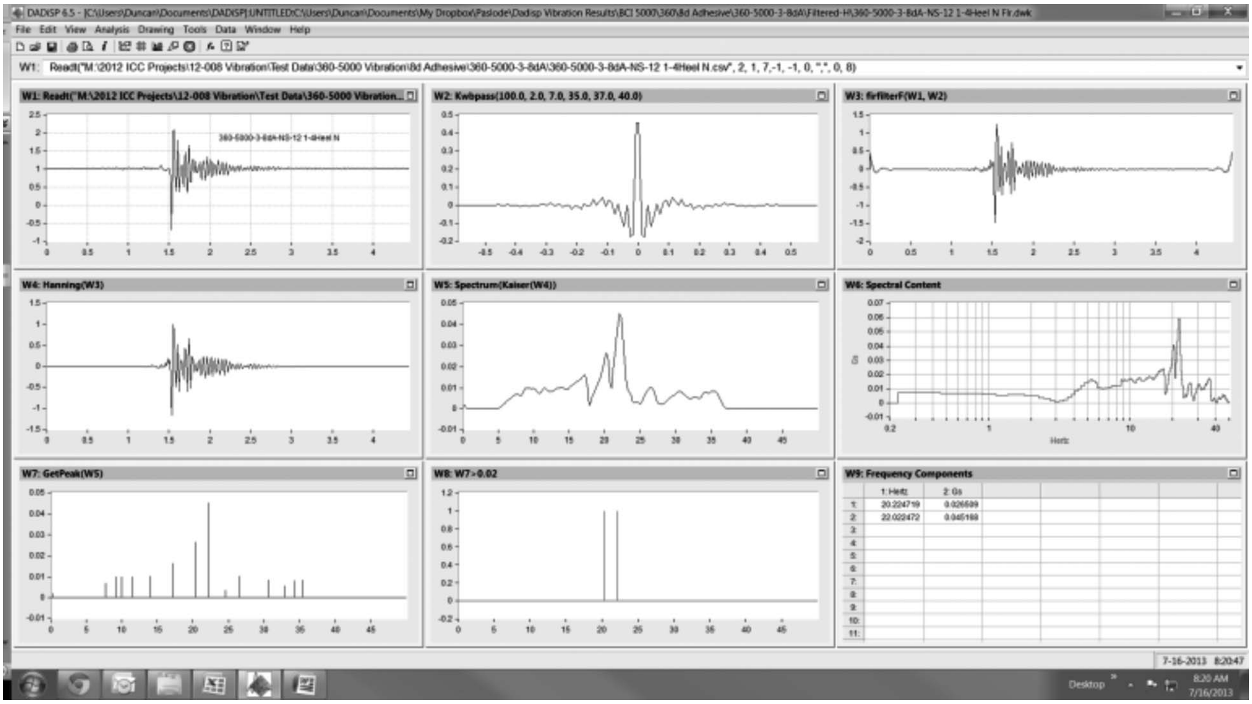
E = modulus of elasticity, MPa (lb/in^2),

I = moment of inertia, mm^4 (in^4), and

L = joist or girder span, mm (in.).

To check on whether the filtering significantly altered the data, the filtered data were plotted over the top of the raw data to see whether significant differences existed. One of these checks is shown in Figure 3. Notice that there is no significant difference in the two lines, the only difference is that the low-power background noise, caused by the other equipment or the surround environment, has been removed.

The primary focus of this article is to compare the fundamental frequencies between specimens with the subflooring attached to joists using 8d common nails, TetraGrip subfloor fasteners, and 8d common nails with an adhesive. In the process of obtaining the data, we questioned whether or not multiple factors would affect the data. Two such questionable factors were whether the age of floor systems and the location of applied load in relation to span would affect the floor vibration performance. To investigate whether a floor response would be affected by a history of cyclic loading to a reasonable expected occupancy load, an aging test was developed where the specimens were subjected to a cyclic load. The effect of this aging test was tested by quantifying the fundamental frequency of a sample of floor specimens and then applying a cyclic load that caused an equivalent moment to that caused by 50 percent of the design live load, and then comparing the frequencies before and after the cyclic loading was applied. The cyclic load was applied for 1,000 cycles. For all samples, the heel drops were performed at three locations along the span of the floor system (1/4, 1/2, and 3/4 span).



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DADiSP 6.5 - [C:\Users\Duncan\Documents\DADiSP\UNTITLED:C:\Users\Duncan\Documents\My Dropbox\Paslode\Dadisp Vibration Results\BCI 5000\360\8d Adhesive\360-5000-3-8dA\Filtered-H\360-5000-3-8dA-NS-12 1-4Heel N Flr.dwk
W1:  Readt("M:\2012 ICC Projects\12-008 Vibration\Test Data\360-5000 Vibration\8d Adhesive\360-5000-3-8dA\360-5000-3-8dA-NS-12 1-4Heel N.csv", 2, 1, 7,-1, -1, 0, ",", 0, 8)
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W9: Frequency Components

	1: Hertz	2: Gs
1:	20.224719	0.026599
2:	22.022472	0.045188
3:		
4:		
5:		
6:		
7:		
8:		
9:		
10:		
11:		

Figure 2.—Typical acceleration analysis for double I-joist floor specimen.

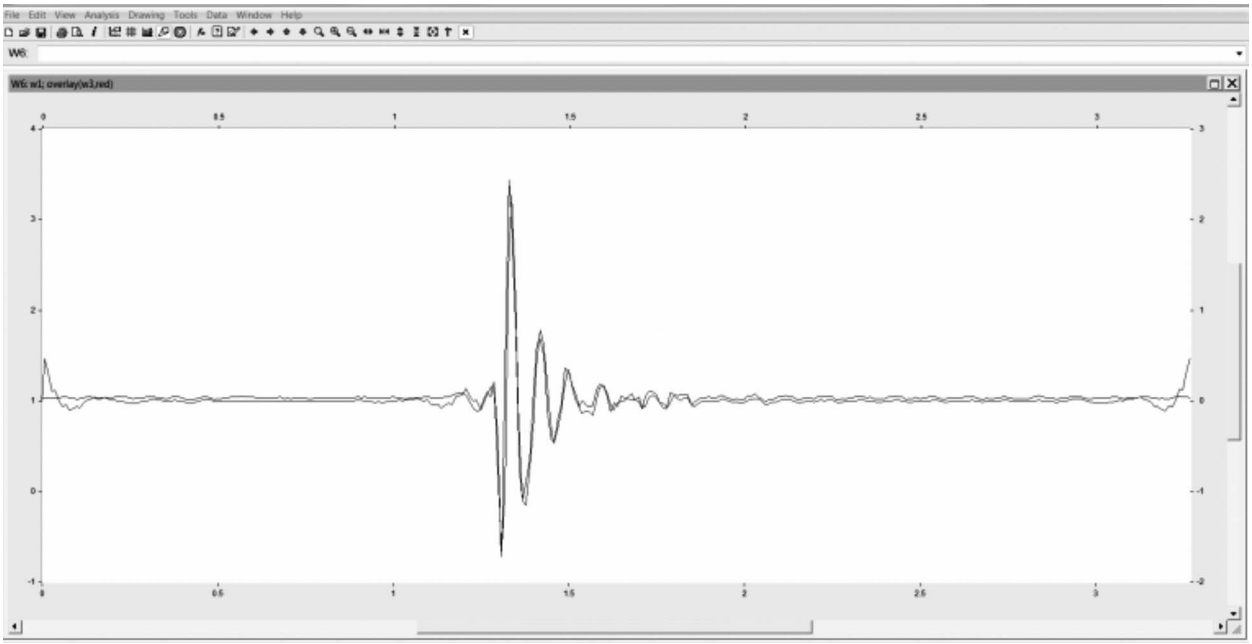

Figure 3.—A typical example of overplotting the filtered and unfiltered data (vertical axis is acceleration and horizontal axis is time).

After the vibration tests were completed, the specimens were loaded monotonically to failure, with loads being applied to the 1/3-span locations. This test was conducted to investigate the performance of the different fastener configurations at strength limit state and quantify the stiffness.

Results and Discussion

Calculated fundamental frequency

During prior research by Dolan et al. (1991), the simple equation shown as Equation 2 was developed that could calculate the fundamental frequency of a given joist. The calculated fundamental frequency with subflooring applied as the only load, yielding the results seen in Table 2. These fundamental frequencies represent an assumption that no composite action between the subflooring and joists exists as a result of the small effective flange widths determined in the previous research (Dolan et al. 1991, Johnson 1994) and the manufacturer's design values were used for the values of E and I.

As seen in Table 2, all configurations have fundamental frequencies greater than the 15-Hz limit criterion for annoying vibration as proposed by Dolan et al. (1991). The testing presented in this article used heel drop to quantify the fundamental frequency to represent practical use conditions. The calculated (expected) fundamental frequencies for the heel-drop tests, which include the weight of the person performing the tests as well as the sheathing, are also shown in Table 2.

Experimental fundamental frequency

The tests to investigate whether aging would affect the vibration response of the floor showed no significant difference in the average fundamental frequencies for the two cases, and it was concluded that the aging protocol had no effect on vibration response. Because this effect was determined to be nonexistent, only two samples were tested with the cyclic loading protocol. All of the other configurations were tested only with the vibration and static bending test protocol.

For all samples, the heel drops were performed at three locations along the span of the floor system. Again, there was no practical difference in the response of the samples due to location of load applied. For further details on these two aspects of the testing, see Duncan et al. (2012b).

Data collected for the three configurations considered—8d common nails, TetraGrip subfloor fasteners, and 8d common nails with adhesive—are presented in Table 3. Each of the sample frequencies in the table represents an average of five specimens. The reader is cautioned about drawing significant conclusions on differences between the configurations. While a couple of the configurations show statistical differences, one must also consider that the mathematics associated with the FFT function used to generate the spectrum of the acceleration traces essentially converts the data in the time domain to a histogram of the data in the frequency domain. This histogram has a resolution or minimum width of each bin into which the data are converted. Because the acceleration traces associated with the heel-drop tests were relatively short, the width of the ''bins'' of the frequency histogram are relatively large (i.e., on the order of 0.5 Hz). Therefore, the fundamental

Table 2.—Fundamental frequencies calculated using Equation 2.

	Fundamental frequency (Hz)	
Configuration	Calculated	Experimental
BCI 5000–L/360	20.8	11.1
BCI 5000–L/480	25.1	13.0
BCI 90–L/360	16.6	10.9
BCI 90–L/480	20.0	12.8

Table 3.—Fundamental frequencies comparing a variety of I-joist configurations and loading at center of span.[a]

		Heel drop	
Joist and span	Assembly configuration	Unsheathed frequency, Hz (COV, %)	Sheathed frequency, Hz (COV, %)
BCI 5000 (L/360)	TetraGrip	**13.7 (2.13)**	**15.0 (8.23)**
	8d nails + adhesives	**13.2 (2.13)**	**14.0 (2.31)**
	Difference	−0.5	−1.0
	Framing difference	−0.5	
BCI 5000 (L/480)	8d nails	**19.5 (5.1)**	20.2 (8.82)
	TetraGrip	**17.6 (2.55)**	19.0 (3.77)
	8d nails + adhesives	**18.**9 (4.76)	19.6 (8.56)
	Difference between 8d nails and TetraGrip	−1.9	−1.2
	Difference due to framing	+0.7	
	Difference between 8d nails and 8d nails + adhesives	−0.6	−0.6
	Framing difference	0.0	
	Difference between TetraGrip and adhesives	1.3	0.6
	Framing difference	−0.7	
BCI 90 (L/360)	TetraGrip	16.2 (3.7)	17.3 (10.5)
	8d nails + adhesives	15.7 (5.8)	16.5 (6.4)
	Difference	−0.5	−0.8
	Framing difference	0.3	
BCI 90 (L/480)	TetraGrip	**14.6 (0.61)**	15.0 (10.5)
	8d nails + adhesives	**14.3 (1.75)**	13.9 (2.45)
	Difference	−0.3	−1.1
	Framing difference	−0.8	

[a] Values are frequencies in Hertz and coefficients of variation (COV) presented in parentheses as percentages. Bold pairs of configurations indicate statistical significant difference.

frequencies determined should be viewed as having a ±0.5-Hz accuracy.

One noticeable trend in Table 3 is that the data have the same trends as found in previous research. The specimens that were configured to represent the deflection criterion L/360 had lower fundamental frequencies than those configured to represent the deflection criterion L/480. This trend occurs because the fundamental frequency is directly proportional to the square root of the bending stiffness of the floor specimen.

In an attempt to isolate the effect of the fastener type from the differences in the framing stiffness, the difference in the framing frequency was subtracted from the difference found in the sheathed condition. As seen in Table 3, the difference in fundamental frequency between the TetraGrip subfloor fasteners and nails plus adhesive is less than 0.8 Hz for floors designed to the L/480 deflection criterion. The difference for the floors designed to the L/360 criterion showed a difference between the TetraGrip subfloor fasteners and adhesives was 0.5 Hz for the BCI 5000 joist and 0.3 Hz for the BCI 90 joist. The same comparisons for the specimens meeting the L/480 design criterion had differences due to fastener type of 0.7 and 0.8 Hz for the BCI 5000 and BCI 90 joist types, respectively. This indicates that the data did not indicate any differences in performance, and the differences shown are not significant from either a statistical or practical point of view. Had a significantly larger sample size been used, it is possible that a statistical difference might have been found, but the practical difference of less than 1 Hz would still be of questionable practical significance. Even when one compares either the TetraGrip subfloor fastener or the adhesive configurations to the 8d common nail configuration, there are no statistically significant differences for the vibration performance.

If one considers the static bending tests that were run to failure, the adhesive did provide higher strengths than the TetraGrip subfloor fastener or the 8d common nail, but at the serviceability level (i.e., annoying vibration) all the fastening systems performed to equal levels. To illustrate why this is, consider Figure 4. The load-deflection curves for each of the samples are plotted on the same graph. Notice that as the deflection increases past about 10 mm (0.4 in.) displacement, the curves for the adhesive configuration begin to diverge from the curves representing the other two configurations. This indicates that a configuration using an adhesive does have higher stiffness and ultimate strength due to improved composite action between the sheathing and framing, but it does not affect the performance until the curvature of the beams becomes significant. If one considers that the magnitude of the deflection associated with vibration is on the order of 5 mm (0.2 in.), the difference in the 15 curves is negligible at this deformation, and therefore, the vibration response between the three configurations should not be significantly different. This is the finding of the vibration testing, and the static bending testing provides additional support to this finding. For further details on the static bending test conducted, see Duncan et al. (2012b).

Finally, the configuration BCI 5000 with L/480 span criteria as shown in Table 3 was tested in a configuration using the 8d common nail without adhesives. The fundamental frequencies for the 8d common nail specimens were significantly higher than either the specimens using the adhesive or the TetraGrip subfloor fastener. When one looks at the data, for some reason, the bare framing fundamental frequencies for the 8d configuration were significantly

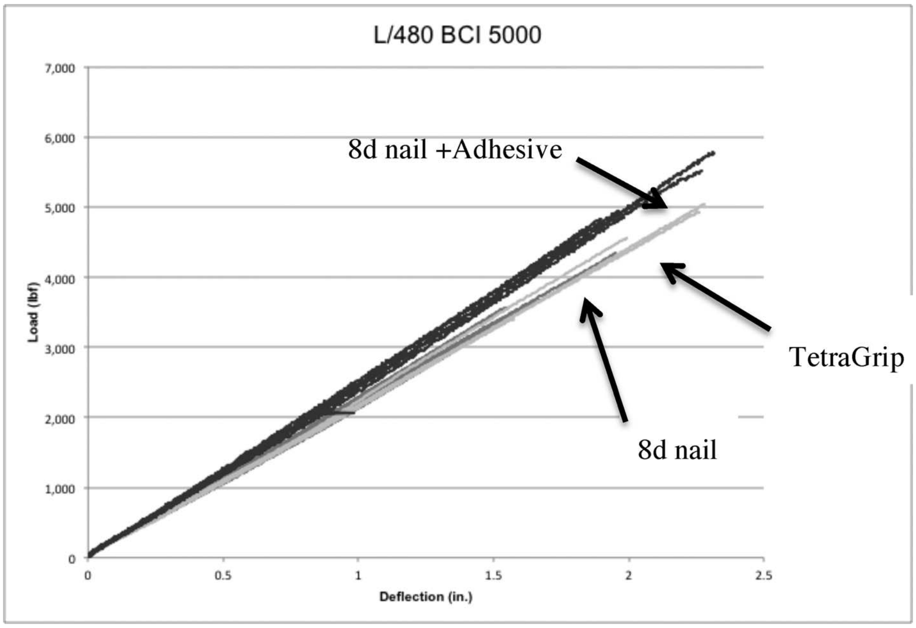

Figure 4.—Load-deflection curve for static bending tests to failure.

higher than the other two configurations, which resulted in the sheathed frequencies being the highest.

Conclusions

Vibration test data results for double-T floor specimens show that when the subflooring is attached using the three tested methods, the vibration response is statistically indistinguishable. The TetraGrip subfloor fasteners performed similarly to the 8d common nails with adhesive for vibration performance for when either an L/360 or L/480 deflection criterion was used for determining the span. The average occupant would not be able to tell the difference in vibration performance between the TetraGrip subfloor fastener and a common nail with adhesive combination when this performance criterion was used.

Static bending tests to ultimate load showed that the TetraGrip subfloor fastener performed similarly to the 8d common nail at the strength limit state, and the specimens using adhesive had higher ultimate strengths. This indicates that while the TetraGrip subfloor fastener does provide performance on par with adhesives for normal occupancy loading, the fastener does not improve the ultimate strength of the floor system as much as adhesives.

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