# Design to Minimize Annoying Wood-Floor Vibrations[1]

by

Frank Woeste and Daniel Dolan

Annoying vibration is probably the most common performance complaint for light-frame wood floors. The 2006 International Residential Code (IRC) and 2006 International Building Code (IBC) do not address the issue of annoying floor vibration, yet the engineer-of-record for a project may face the issue at the design stage, or the consulting structural engineer may be engaged to determine the cause of an annoying vibration problem in a dwelling designed and built under the prescriptive provisions of the IRC. While wood floor vibration is not typically a structural safety issue, it deserves attention by the design professional at the design stage because an annoying floor vibration problem can be costly or practically impossible to fix.

The purpose of this article was to provide analysis tools and rules-of-thumb for the design professional to *minimize* annoying vibration problems in light-frame commercial wood-floors, and to provide guidance in diagnosing problems in residential applications. We used the word "minimize" in the objective statement to emphasize the fact that human occupants will respond differently to in-service floor vibrations—some may feel nothing while others may be very uncomfortable. It may be prudent for the design professional to discuss this subject with the owner at the project planning stages.

**The** design approach described in this article offers a good mechanism to communicate to the owner three aspects of floor design:

a) annoying vibrations are possible when floors are designed to the building code minimum,

b) the threshold of what's annoying is subjective, and

c) various steps can be taken to prevent the likelihood of annoying vibrations, probably with minimal added costs.

Research at Virginia Tech on full-scale solid-sawn joists, I-joist, and metal-plate-connected (MPC) floor trusses in the 90's addressed the issue of wood floor

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[1] A draft of this document was published as Woeste, F. and D. Dolan. 2007. Is a "spring in your step" causing problems? **Structural Engineer** 8(5): 24-27.

vibration control. The laboratory testing program and field validation of a simple design rule were limited to wood joist floors with structural wood panel sheathing, thus the typical design dead load was either 10 psf for solid-sawn and I-joists test cases or 15 psf for 4x2 floor trusses. Results presented in this article may not apply to wood-floor applications with one or two inches of concrete because of the change in stiffness, mass, and composite action involved. Wood floors with substantial mass need to be analyzed for vibration due to impulses from ordinary foot traffic differently, and thus the equations and rules-of-thumb presented in this article do not directly apply to wood-floor constructions with a concrete topping or other elements that raise the design dead load to more than 15 psf. Analysis of floors with relatively high mass should use different equations such as those used for steel and concrete floors as described in the Manual of Steel Construction.

## Basics of Wood-Joist Vibration Analysis

Analysis of light-frame wood floors starts with estimating the natural period of the floor system. This is done by considering a strip of floor that includes a single joist and the tributary sheathing material, assuming a simply-supported beam.

### Joist Fundamental Frequency

**The** fundamental frequency of joists can be calculated using the equation developed by Murray (1991):

$$f = 1.57\sqrt{\frac{386EI}{WL^3}} \qquad \text{(Equation 1)}$$

where: $f$ is the fundamental frequency of the joist in Hz,
$E$ is the modulus of elasticity in psi,
$I$ is the moment of inertia in inches$^4$,
$W$ is the total supported permanent (dead) load in lbs, and
$L$ is the joist span in inches.

It should be noted that *W is the actual dead load*, which can be substantially less that the *design* dead load for light-frame wood construction.

<u>Research Results</u>

**We** tested 13 full scale floors (16'x16') at Virginia Tech constructed with joists (solid-sawn, I-joists, and floor trusses) at 16-inches o.c.

In all cases, the joists were sheathed with 23/32" rated T&G floor sheathing. On each end, the joists were attached to a 2x6 sill plate that was connected to a short concrete block wall. Each floor was "excited" by dropping a weight, and the dynamic response variables were recoded by electronic means. A human subject was located in the center of the floor on a chair, and the subject recorded when vibration was detected.

**An** additional 73 in-situ floors were evaluated using heel drop tests with second-party evaluation of annoyance. These floors were tested as <u>empty rooms</u> as well as <u>furnished rooms</u> to validate the design criteria.

<u>Research Results Summarized</u>

**Based** on the VT vibration research program led by Dr. Dolan and executed by several graduate students, the following design/evaluation criteria resulted:

Pass criteria: Empty floor, $f \geq 15$ Hz

Furnished room, $f \geq 14$ Hz

<u>General Vibration Design Principles</u>

**Occupants** are very sensitive to vibrations in the range of *7-10 Hz*. In theory, joist designs (or floor system designs) that vibrate well above 7-10 Hz should be judged by the occupants as acceptable simply because they can't feel the higher frequencies.

**As** a general rule, wider joist spacing (24"o.c. versus 12"o.c.) will produce a higher frequency because deeper members, having a greater bending stiffness (EI), will be required to meet building code deflection requirements.

It's better for a foot to impact a joist with a larger EI--the direct result of a wider joist spacing.

Live Load and Deflection Limit

The 2006 IRC permits a design live load of 30 psf for "sleeping rooms."

**As** will be demonstrated later, the 30 psf limit for sleeping rooms can be a *unintended* source of vibration problems in one-and-two family dwellings.

The IRC specifies 40 psf for all other rooms. In modern construction and homes, "sleeping rooms" are used as offices, exercise rooms, play rooms, and so on, thus the concept of a single purpose sleeping space is outdated. Depending upon the occupancy, the IBC (2006) specifies various uniform live loads and in some cases concentrated loads for sizing the joists. Typical design live loads range from 40 to100 psf. The higher design live loads are beneficial to preventing annoying floor vibrations because the resulting designs will typically have a greater bending stiffness, EI, and therefore, higher fundamental frequency (Equation 1).

Example Frequency Calculation—Rigid Joist Supports

**Of** the calls we receive on floor vibration, the most common scenario stems from the use of 30 psf live load, L/360 live-load deflection limit, and joists at 12" o.c. Perfect design for long span!

Assuming rigid (but simple beam) end supports, such as bearing on a block or concrete stem wall, Equation 1 can be used to predict the natural frequency of the joist. From the 2003 IRC, Table R502.3.1(1), a 2x10 No. 2 SPF floor joist will span 19'-0". For light-frame construction, design *span* is defined by convention to be the clear span, from face-of-support to face-of-support[2]. For this example, assume the *actual* dead weight of the floor to be 7 psf for the joists, floor sheathing and carpet. Referring to the AF&PA (2005) NDS Supplement, E is obtained from page 35 and I is tabulated on page 14.

**The** required input data for a 2x10 No. 2 SPF joists at 12"o.c. are:

$E = 1{,}400{,}000$ psi $\quad I = bd^3/12 = 98.93 \text{ in}^4 \quad L = 19' \times 12 \text{ in/ft} = 228"$

$W = [19.0 \text{ ft.} \times (12"/12"/\text{ft.})] \times 7 \text{ psf (actual dead)} = 133 \text{ lbs.}$

[2] In general, span is defined by NDS 2005, Section 3.2.1 as distance from face-to-face of supports, plus ½ the required bearing length at each end.

Substituting the data into equation 1 yields:

$$f = 1.57\sqrt{\frac{386 * 1{,}400{,}000 * 98.93}{133 * 228^3}} = 9.1\ Hz$$

**Thus**, the calculated frequency is near the *middle* of the most sensitive range of vibration for humans (7-10 Hz).

The example calculation demonstrates how a "code conforming" floor can be problematic with respect to annoying vibration.

**At** least for lower live loads, closely spaced joists at allowable *maximum* span may produce objectionable floors.

System Effects on Joist Vibration

**When** a joist bears on another beam (girder) with a separate stiffness and natural frequency, the two interact to produce a theoretical combined frequency.

The fundamental frequency of the joists is affected by the vibration of their supports, and therefore, the frequency of the joists and any girder used to support the joists must be combined using the equation:

$$f_{system} = \sqrt{\frac{f_{joist}^2 * f_{girder}^2}{f_{joist}^2 + f_{girder}^2}} \qquad \text{(Equation 2)}$$

As discussed earlier, full scale laboratory tests of joist floors having "rigid" bearing supports led to the conclusion and recommendation that joists with the same bearing conditions should have a fundamental frequency of at least 15Hz at the design stage to minimize the possibility of "annoying vibrations."

**Assuming** however the same joists are supported by a flexible girder having the same natural frequency of 15 Hz, the combined theoretical frequency is much less than 15 Hz.

**For** example, when $f_{joist}$=$f_{girder}$=15Hz, the system equation yields:

$$f_{system} = \sqrt{\frac{15^2 * 15^2}{15^2 + 15^2}} = 10.6 \text{ Hz} < 15\text{Hz}$$

**The** instructive aspect of this formula is valuable—a system may produce "annoying vibrations" while each of the components could have a natural frequency not detectable by most occupants (most sensitive to 7-10 Hz).

The system Equation 2 also provides insight into possible causes of annoying vibration not linked to the actual joist design properties or girder design properties. For example, a solid-sawn joist may have "twist" and as a result the joist bearing on top of the girder might only be on one edge of the narrow face of the joist. This condition could add additional "spring action" to the joist-to-girder connection. Another example is a joist face-mounted to the girder with the joist not securely seated in a joist hanger or the hanger itself is not installed per the manufacturer's recommendation. To summarize, any construction deficiency that compromises the *apparent* design stiffness (EI) of the joist when connected to the floor girder may negatively impact $f_{joist}$ and thus cause the system to vibrate in the sensitive range. Because of the complexity of actual constructions and the variability of materials, the root cause(s) of a vibration problem can be misdiagnosed, and thus the repairs deemed necessary may not cure the problem. Knowing the potential difficultly of solving annoying vibration problems in a completed structure, the project design professional should have ample motivation to address the vibration issue at the design stage.

**We** attempted to apply Equation 2 to typical joist-girder construction and found that it was not practical to achieve a predicted system frequency of 15 Hz for residential applications, and thus designer judgment is needed in every case and application.

**For** residential girders, we have recommended the use of L/600 when coupled with good construction practices for solid-sawn, I-joist, and floor trusses.

Experience with designs that perform well in a residential application (such as a single foot fall) may not carry over to the general non-residential case because of differences in the dynamic loads involved. In general, the project design professional for all projects must rely on their own design experience, product and research information, and manufacturer's recommendations while taking into account the performance expectations of the client.

### Good Practices for Residential Applications

We realize that *Structural Engineer* magazine is devoted to engineered construction and that residential floors are not typically designed by a structural engineer. However, since structural engineers are often called upon to evaluate and possibly design repairs to annoying vibration problems in residential applications, we offer some rules of thumb or good practices for the residential case.

## General Rules-of-Thumb

### **Use** a Live Load of at Least 40 psf

The IRC permits a 30 psf live load for "sleeping rooms", but when this lower load is used in design, the joists will generally be more flexible and more likely to produce annoying vibrations.

### **Increase** the Joist Depth by One Size

If the code requires a 2 by 8 joist at 16 inches o.c., then use a 2 by 10 joist of the same grade, species, and spacing, or a 14-inch-deep floor truss when a 12-inch-deep truss would meet code requirements. This rule should provide good results when used in conjunction with a 40 psf live load. (Using a smaller allowable deflection limit such as L/600 also results in similar changes to the floor framing.)

### **Glue** and Screw the Sheathing

Floor sheathing should always be glued and screws work better than nails for long-term bounce control. Reducing the on-center spacing—from 16 inches to 12 inches, for example—is probably the least efficient way to improve floor performance. Occupants feel "bounce" as the result of a foot impacting an individual joist, and even at 12 inches o.c., the joists are not close enough for the shock of a foot to be carried by two joists.

## Rules-of-Thumb for Solid-Sawn, Wood Truss, and I-Joist Floors

### Solid-Sawn Joists

In 1964, the Federal Housing Administration published *Minimum Property Standards for One and Two Living Units,* which recognized that solid-sawn joist spans over 15-ft. in length may be inadequate to prevent annoying floor vibration. The agency proposed a rule limiting live-load joist deflection on a graduated scale from *L*/360 at 15 ft. to *L*/480 at 20 ft., and a total deflection of no more that 0.5-inch for spans over 20 feet. These recommendations are conservative and show that the floor vibration problem is not a new one, dating back at least four decades.

**We** proposed a simple rule-of-thumb for the design of solid-sawn joists up to 20 ft. in length (a practical maximum span):

- Use 40 psf live-load and a live-load deflection of L/480 for joist spans up to 20 ft.

This rule is very easy to remember, and it can be easily applied to span tables based on an *L*/360 deflection limit.

**As** it turns out, a maximum joist span under a *L*/360 live-load limit can be conservatively reduced to a maximum joist span under a *L*/480 live-load limit by multiplying the maximum L/360 span by 0.91.

### 4x2 MPC Floor Trusses

**An** important step in preventing annoying vibrations in floor truss systems is the application of a strongback.

Strongbacks control annoying vibrations by stiffening the impacted floor truss, which causes it to vibrate at a higher frequency. As discussed earlier, a higher frequency is desirable because the occupants will not likely feel vibrations.

****See page 3 of the next JLC publication for strongback details****

**Beyond Code: Preventing Floor Vibration**
by Frank Woeste, P. E., and Dan Dolan, P. E.

## Wood I-Joists

Preventing annoying I-joist vibration is generally more complicated than for other joist types.

**Our** best advice is to consult the I-joist manufacturer on the subject of vibration control.

One I-joist manufacturer, Trus Joist (now part of Weyerhaeuser's iLevel business), conducted extensive testing of floor performance and developed the proprietary TJ-Pro Rating system. Using their TJ-Beam software, a user can select a TJ-Pro Rating between 20 and 70, with higher values offering greater levels of protection against potential floor vibration problems as judged by an occupant[3]. This system allows the homeowners, through their contractors or architects, to select the level of floor performance that meets their expectations.

### Summary

Design to prevent annoying vibrations is not covered by the building codes, yet it can be a very important issue for the owner and building occupants. We have summarized our research findings at Virginia Tech University on light-weight floors (design dead load up to 15 psf) and listed some rules-of-thumb for minimizing complaints of annoying vibration in residential applications.

**Communication** with the owner on the vibration issue is important at the project planning stage when it is possible to incorporate levels of protection against annoying vibrations into the floor system design.

### References

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[3] For example, the designer can select a floor design that would satisfy 98% of the population.

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# Beyond Code: Preventing Floor Vibration

by Frank Woeste, P. E., and Dan Dolan, P. E.

Floor vibration, or bounce, is not a safety issue — it's a performance issue, and one that's likely to be important to homeowners. No one likes to hear the china rattling in the cabinet when they walk across the room. But at what point is the floor stiff enough, and how can a builder predict how the floor will perform?

Unfortunately, there's no clear-cut rule for a builder to follow, and the physics of vibration are so complicated that it's no easy matter to design a guaranteed bounce-free floor (see "Sizing Stiff Floor Girders," *Practical Engineering*, 8/97). Also, "acceptable" floor performance is highly subjective: What's good enough for one homeowner may not be good enough for another.

The building codes don't help much in this regard. They're primarily concerned with safety — in other words, the strength of the beam rather than its stiffness. The most stringent code limit for joist deflection is 1/360 of the span: For example, a joist with a clear span of 15 feet must not deflect more than 1/2 inch under live load (people and furniture). The dead load — the weight of the floor materials — is not typically included in calculating deflection.

And yet it has been known for decades that a span/360 live-load deflection limit will not necessarily yield floors that are acceptable to everyone when it comes to vibration.

The purpose of this article is to provide some simple rules of thumb for taking the annoying vibrations out of floor

## Table 1. Maximum Clear Spans (Lmax) for Joists Longer than 15 Feet (deflection limited to 1/2 inch)

| Lcode | Lmax | Lcode | Lmax | Lcode | Lmax | Lcode | Lmax | Lcode | Lmax |
|---|---|---|---|---|---|---|---|---|---|
| Less than 15-0 | Same as Lcode | 16-0 | 15-9 | 17-0 | 16-5 | 18-0 | 17-2 | 19-0 | 17-11 |
| 15-1 | 15-0 | 16-1 | 15-9 | 17-1 | 16-6 | 18-1 | 17-3 | 19-1 | 17-11 |
| 15-2 | 15-1 | 16-2 | 15-10 | 17-2 | 16-7 | 18-2 | 17-3 | 19-2 | 18-0 |
| 15-3 | 15-2 | 16-3 | 15-11 | 17-3 | 16-7 | 18-3 | 17-4 | 19-3 | 18-1 |
| 15-4 | 15-3 | 16-4 | 15-11 | 17-4 | 16-8 | 18-4 | 17-5 | 19-4 | 18-1 |
| 15-5 | 15-3 | 16-5 | 16-0 | 17-5 | 16-9 | 18-5 | 17-6 | 19-5 | 18-2 |
| 15-6 | 15-4 | 16-6 | 16-1 | 17-6 | 16-10 | 18-6 | 17-6 | 19-6 | 18-3 |
| 15-7 | 15-5 | 16-7 | 16-2 | 17-7 | 16-10 | 18-7 | 17-7 | 19-7 | 18-3 |
| 15-8 | 15-6 | 16-8 | 16-2 | 17-8 | 16-11 | 18-8 | 17-8 | 19-8 | 18-4 |
| 15-9 | 15-6 | 16-9 | 16-3 | 17-6 | 17-0 | 18-9 | 17-8 | 19-9 | 18-5 |
| 15-10 | 15-7 | 16-10 | 16-4 | 17-10 | 17-1 | 18-10 | 17-9 | 19-10 | 18-6 |
| 15-11 | 15-8 | 16-11 | 16-5 | 17-11 | 17-1 | 18-11 | 17-10 | 19-11 | 18-6 |

*For code spans 20-0 and greater, $L_{max}=(180\ L^3_{code})^{0.25}$, where Lcode is in inches.

Limiting joist deflection to 1/2 inch is an effective way to reduce annoying floor vibrations. For spans longer than 15 feet, the code L/360 maximum deflection limit results in actual deflections greater than 1/2 inch. In this chart, numbers in the red columns represent code-allowable joist spans (in feet-inches) assuming a deflection limit of L/360. In the blue columns, those spans have been reduced so that the actual deflection is limited to 1/2 inch. To use this chart, locate your required clear span in the blue columns. Then, using a span table designed for L/360 maximum deflection, 40 psf live load, and the appropriate dead load, find a joist size and species that will work for the corresponding number in the red column. Your joist will then be sized to limit live load deflection to 1/2 inch.

## Table 2. Expected Vibrational Performance of Residential Floor Trusses (40 psf Live Load)

| Live Load Deflection Limit | Strongback Installed | Truss Spacing (inches) | Vibration Rating |
|---|---|---|---|
| Span/360 | No | 24 or less | Code minimum; not rated |
| Span/360 | Yes | 24 or less | Good* |
| Span/480 | No | 24 or less | Good* |
| Span/480 | Yes | 24 or less | Very Good* |

*Ratings require a minimum 23/32" APA-Rated sheathing, glued to truss chord and using nails or screws, and span-to-depth ratio of 20 or less. Ratings apply to maximum spans at the tabulated deflection limit. The ratings are based on specific input from experienced wood-truss design professionals, and our interpretation of opinions of experts and case studies.

systems, whether you're framing with solid-sawn joists, metal-plate-connected floor trusses, or wood I-joists. There's no guarantee that every customer will be satisfied if you follow these guidelines, but they should prevent the vast majority of complaints.

### Some Quick Rules of Thumb

Before looking at specific types of joists, here are some general guidelines for controlling bounce.

✔*Shorten the span.* In general, shorter spans make for stiffer floors. For example, if the L/360 span table tells you a joist of a given size, grade, and species will just barely work for your span, shorten the span by adding a girder near the center of the original span. The resulting floor will vibrate less.

✔*Increase the joist depth one size.* If the code requires a 2x8 at 16 inches on-center, then use a 2x10 of the same grade and species. Or use a 14-inch-deep floor truss when a 12-inch deep truss would meet code requirements. This may not be the most cost-effective solution in every case, but it's easy to remember and will save time and worry.

Probably the least efficient way to improve floor performance is to reduce the on-center spacing — 16 inches to 12 inches, for instance. Occupants feel "bounce" as a result of a foot impacting an individual joist. But even at 12 inches on-center, the joists are not close enough for the shock of a foot to be carried by two joists.

✔*Glue and screw the sheathing.* Floor sheathing should always be glued down. Screws work better than nails for long-term bounce control.

### Design for Solid-Sawn Joists

Our recommendation for stiffening solid-sawn floors is a simple modification of a rule that was published in 1964 by the FHA: For floors up to 15 feet, limit live-load deflection to span/360; for spans over 15 feet, limit the live-load deflection to 1/2 inch (see Table 1, page 69). In adopting this rule, we encourage builders and designers to ignore the reduced live load of 30 psf for sleeping areas, and instead use the standard 40 psf live load for all rooms. After all, a bedroom can become a study or home office, and the traffic may be heavier than in a living room.

### Metal-Plate-Connected Floor Trusses

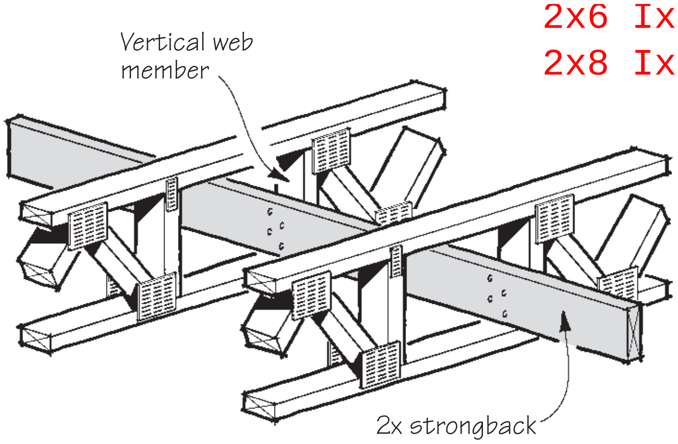
Floor trusses are a unique product in that they accommodate effective strongback bracing (see *On the House,* 7/98, for more on strongbacks). The consensus among wood truss professionals is that strongbacks are effective in minimizing annoying vibrations, and that they are well worth the time and money it takes to install them.

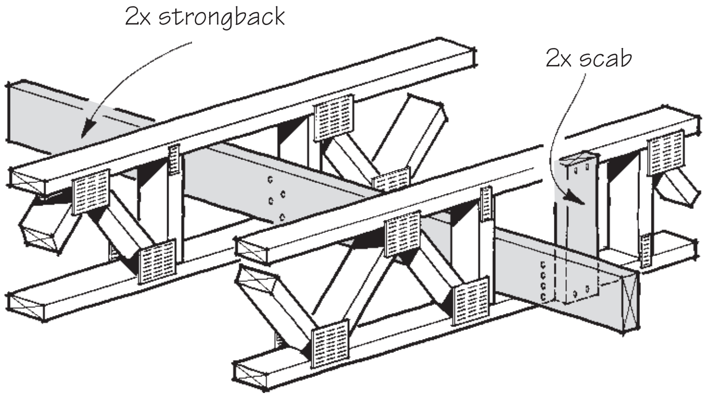
Table 2 illustrates the expected performance of various floor truss designs, using a 40-psf live load. Table 3 gives guidelines for sizing and installing strongbacks. For best performance, strongbacks should be installed near the center of the span (versus two at the third points) in upright position and attached to a vertical web. The strongback should also be located at the bot-

## Table 3. Sizing and Attaching Strongbacks

| Clear span | Strongback size | Connection requirement at each truss web (minimum) |
|---|---|---|
| Greater than 15 feet, but less than or equal to 20 feet | 2x6 | 4-16d Box (0.135"x3.5") |
| Greater than 20 feet | One 2x8 (or 2 2x6s) | 8-16d Box (0.135"x3.5") |

2x6 Ixx=20.8
2x8 Ixx=47.6




Strongbacks should be securely attached to a vertical web member at center span next to the bottom chord (top illo). If the vertical web members don't line up properly, you can attach a 2x4 or 2x6 scab from chord to chord and nail the strongback to the scab (above illo). To transfer the load, use as many nails to attach the scab as you use to attach the strongback (see chart).

tom of a vertical web. To be effective, the strongback must be snugly attached to each web, as indicated by the nailing recommendations in Table 3.

When, for whatever reason, the vertical webs don't line up, you can attach a 2x4 or 2x6 scab to the top and bottom chords for attaching the strongback to the truss (see illustration). The total number of nails used to attach the scabs to the truss chords should match the number used to attach the strongback to the vertical web.

Some of the truss professionals that we interviewed when developing Table 2 had more restrictive rules to offer, but none had less restrictive design advice. Again, no design criteria is guaranteed to totally eliminate vibrations, but we believe that following the recommendations in the table will minimize complaints.

### Wood I-Joists

When using wood I-joists, a simple way to get good results is to always use the tables designed for span/480 deflection. Any I-joist stamped under the new APA standard for performance rated I-joists is automatically designed to meet the span/480 limit. The standard also uses 40 psf as the minimum live load for any floor. The APA standard is now being used by some I-joist manufacturers to make selection of I-joists easier. The allowable spans for various spacings are printed right on each joist.

Another design system for control vibration in wood I-joist floors is Trus Joist MacMillan's TJ-Beam software. Trus Joist has done extensive testing of floor performance and has developed its own rating system. Using the software, a user can select a number between 20 and 70, with 70 offering the greatest level of protection against potential floor problems as judged by an occupant. For example, a design that is rated at 55 is expected to be judged as "Good to Excellent" by 96% of the population, while 2% should judge such floors as "Marginal," and 2% should judge the floor to be "Unacceptable." This system allows the homeowners, through their contractors or architects, to select the level of floor performance to meet their expectations.

We tested the software for a 16-foot clear span supported by 2x4 walls (16 ft. 7 in. outside-to-outside), with I-joists 16 inches on-center and a residential load of 40/12 (live load/dead load). Using a 9.5-inch TJI Pro-250, the rating was 35. Increasing the depth to a 14-inch TJI Pro-250, the rating was a 53. Tightening up the spacing of the 9.5-inch I-joist to 12 inches on-center increased the rating only to 42 — illustrating that going to a deeper joist at the same spacing is a better solution.

The TJ-Beam software also provides a relative cost index that tells the user how much extra an improved floor will cost. Often an improved performance design can be obtained with the same or even lower cost than the original design.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# Thank you!


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