Serviceability of Floor Systems in Existing Residential Timber Frame Structures

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Abstract

This paper presents three case studies involving the serviceability of floor systems in existing residential timber framed structures. The problems identified with these floor systems included “bouncy” floors, swaying furniture, rattling decorative items placed on furniture, and rattling noises.

Descriptions of the evaluation of these floor systems are presented including results of calculations and physical dynamic testing and by comparison of those results to available serviceability criteria. Criteria used included span to deflection ratios, point load deflections, system natural frequency, and manufacturer specific ratings.

A range of solutions implemented for these cases is presented that includes both structural and non-structural measures. Conclusions are reached regarding the applicability of available design criteria in these case studies as well as the difficulty in applying design criteria to an issue that is subjective to occupant sensitivity.

Introduction

The expected serviceability of floor systems can generally be predicted during their design. However, actual satisfaction with a particular system can be affected by a number of factors which the designer may have little or no control over. These factors include: 1) construction techniques or quality, 2) floor finishes, 3) floor loading and load arrangement, and 4) occupant perception. The difficulty in balancing the consideration of these many factors against generating an easy to use design guideline has been somewhat elusive as demonstrated by the published literature and documented research. In addition, the availability in recent years of engineered wood products has allowed the design of systems with longer spans and shallower depths. Until recently, these products allowed for residential spans outside the range of those tested. This paper describes three case studies involving long span wood framed floor systems and compares the performance of these systems to available serviceability criteria.

Serviceability Criteria

Review of available research relating to the dynamic acceptability of timber frame floors revealed a number of different criteria for serviceability assessment of floor systems (Dolan and Kalkert, 1994). Several criteria presented below include span to deflection ratio, point load deflection, system natural frequency, and manufacturer specific rating. A discussion of these criteria is presented below.

SPAN TO DEFLECTION RATIO

One of the most basic guidelines is the span to live load deflection ratio. As an indirect serviceability criterion, this guideline has been in the building codes for many years. However, recent modifications have been suggested in an attempt to use this guideline to address serviceability issues in wood framed residential floor systems. These modifications propose to limit the live load deflection to L/360 for spans less than 4.57 m (15 ft.) or L/480 for spans over 4.57 m (15 ft.) (Woeste, 1996). In general, however, the span to deflection ratio based on a uniformly distributed load has not been shown to be the best predictor of a system’s serviceability performance.

POINT LOAD DEFLECTION

The National Building Code of Canada, Part 9, as modified in 1997 for engineered wood products identifies limits to the mid-span joist deflection for a simple span joist with a concentrated 1 kN (225 lb.) load placed at its mid-span. These limits are summarized below.

$\Delta \leq 2.0$ mm - spans under 3.0 m

$\Delta \leq 8.0 / L^{1.3}$ mm - spans from 3.0 m to 5.5 m

$\Delta \leq 2.55 / L^{0.63}$ mm - spans from 5.5 m to 9.9 m

$\Delta \leq 0.6$ mm - spans beyond 9.9 m

$\Delta \leq L / 360$ - all spans (distributed load of 1.9 kN/m^2 (40 lbs/ft^2)

Aside from the span to live load deflection ratio, this criterion appears to be the most widely accepted and applicable to a wide range of spans and joist types.

In determining the deflection of the floor joist assembly for a concentrated load it is important to consider load sharing of adjacent joists as well as possible composite action of the floor sheathing. Load sharing with adjacent joists is significantly affected by the presence of bridging between the floor joists and the stiffness of the floor sheathing or topping (Hu and Tardif, 2000), (Taylor and Hua, 2000).

SYSTEM NATURAL FREQUENCY

A criterion to limit the natural frequency of timber framed floors has also been proposed (Johnson, 1994), (Runte, 1993), (Dolan, 1994). This criterion, based on laboratory and in-situ testing, limits a floor system's first mode of vibration to a frequency of 15 Hz. The formula to determine the first natural frequency of a simple span beam with uniformly distributed mass is given below.

$$f = 1.57 \left[\frac{gEI}{WL^3} \right]^{1/2} \text{ Hz}$$

Where g is the acceleration due to gravity, E and I are the material and section properties of the joist, and W is the total weight supported by the beam. The total weight is equal to the uniform dead load (w) multiplied by the beam length (L) and the beam spacing (s).

Although this criterion generally ensures systems with acceptable serviceability performance, it becomes restrictive for wood framed systems when it is extrapolated to longer span floor systems as shown below.

Substituting the midspan deflection of a uniformly loaded joist,

$$\Delta_{DL} = \frac{5WL^3}{384EI} \text{ or } \frac{EI}{WL^3} = \frac{5}{384\Delta_{DL}}$$

into the frequency equation produces a relation between the frequency and the dead load deflection after some rearrangement as shown below.

$$f = 1.57 \left[\frac{5g}{384\Delta_{DL}} \right]^{1/2}$$

$$\Delta_{DL} = \frac{315}{f^2} \text{ mm or } \Delta_{DL} = \frac{12.4}{f^2} \text{ in.}$$

Placing a lower bound limit of 15 Hz on the system frequency restricts the system's dead load deflection to 1.39 mm (0.055 in.) regardless of span length. Equivalently, the live load deflection would also be limited to a set value regardless of span. Therefore, this frequency criterion essentially sets the span to deflection ratio directly proportional to the span.

As an example, for a typical dead load of 0.38 kN/m^2 (8.0 lbs/ft^2) and a live load of live load 1.9 kN/m^2 (40 lb./ft.^{2}), the live load deflection would be limited to 6.95 mm (0.275 in.) for all spans. This criteria is therefore more restrictive for longer spans than other proposed criteria.

MANUFACTURER SPECIFIC RATING

Trus Joist MacMillan has developed a rating system for floor assemblies designed using their TJM structural products. This rating system was developed using floor assembly research, proposed serviceability criteria and dynamic theory calibrated using floor performance surveys of occupied floor systems. The rating system provides an estimate of an occupant's judged acceptability for various floor system configurations. The TJ-Beam™ software employs the rating as the user chooses specific product solutions. This allows the user to consider serviceability within a group of structurally acceptable solutions. The rating can also be modified for such things as bridging, ceiling type, flooring overlays and partitions. A discussion of floor performance and the TJ Pro™ Rating System is provided in the documentation of the TJ-Beam™ Software.

Case Studies

CASE STUDY #1

The first case study involves eight single-family detached production residential structures. The living room and kitchen of these units are supported by this floor system with the garage below. The kitchen island was located with its long axis parallel to the trusses at about one-third the truss span from the support. No significant partitions occur above or below this system. Several owners of homes with this design complained of excessive floor vibrations and swaying of the kitchen islands.

This floor system is composed of 286 mm (11.25 in.) deep open web trusses spaced at 406 mm (16 in.) on center and spanning 5.64 m (18.5 ft.). The floor sheathing is 15.9 mm (0.625 in.) oriented strand board. The ceiling consists of two layers of 15.9 mm (0.625 in.) gypsum board. The floor also contains fiberglass insulation as well as ventilation piping and electrical lines. The total weight of the floor system with flooring is estimated at 0.48 kN/m^2 (10.0 lb./ft.^{2}).

A review of the truss shop drawings showed that the trusses met or exceeded the Uniform Building Code requirements for allowable stress. The trusses were designed for a live load of 1.9 kN/m^2 (40 lb./ft.^{2}). No bridging was specified between the joists.

The floor system was investigated by both visual and physical testing. Visual observations were made after removing the ceiling in one garage. The floor system was found to be installed and fabricated according to the manufacturer's specifications and design assumptions. Vibration tests were performed at seven homes using a frequency controlled oscillating mass and accelerometers connected to the floor as shown in Figure 1. The recorded first mode of vibration varied among the units from 10.5 to 12.8 Hz depending upon flooring and the type and configuration of furniture (see Figure 2).

Figure 1 - Frequency Controlled Oscillating Mass Used to Measure Frequency Response in Floors

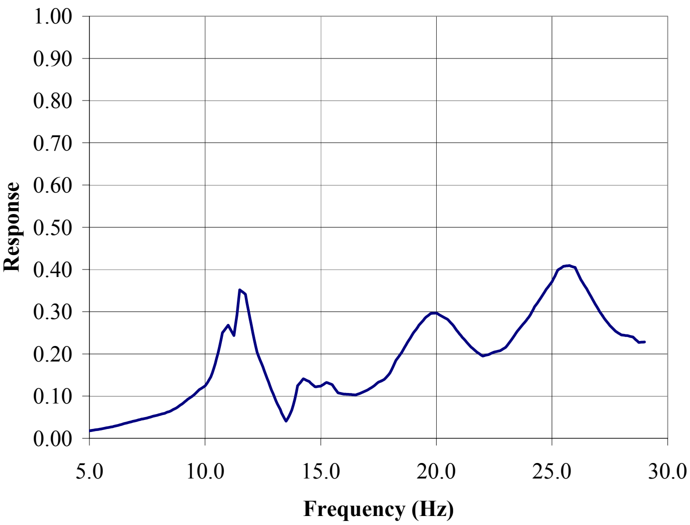

Figure 2 – Graph of Frequency Response from Random Excitation Shaker on Original Floor

The following is a comparison of this floor system to the serviceability criteria described above. The computed live load deflection was L/600 neglecting any composite action from the floor sheathing. This indicates that the system exceeds the span to live load deflection ratio criterion. The computed ratio would be even better for this system if the partial composite action of the floor sheathing were considered (Fridley and Rosowsky, 1994).

This floor system does not meet the 1kN (225 lb.) point load deflection criterion of the National Building Code of Canada as modified in 1997. This criterion would have required a mid-span deflection of 0.86 mm (0.034 in.) for this span. The comparable deflection for this floor system was calculated to be 1.8 mm (0.07 in.), more than twice the allowable deflection. The calculated deflection considered only two floor joists since no bridging was present in the floor system.

Finally, this floor system did not meet the 15 Hz natural frequency criterion since its first natural frequency was calculated to be 11.5 Hz and measurements ranged between 10.5 and 12.8 Hz.

It was decided to retrofit the floor to improve its serviceability performance. Due to ceiling height limitations and the presence of mechanical, electrical, and plumbing running within in the floor system, the retrofit scheme chosen consisted of adding 2x6 members flat under the 2x4 bottom chord of the truss as shown in Figure 3.

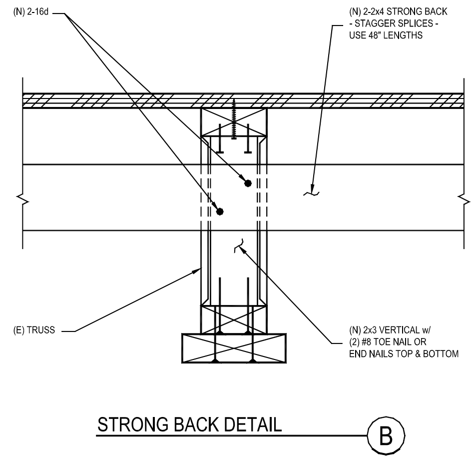

Figure 3 – Detail of Stiffened Floor Joists

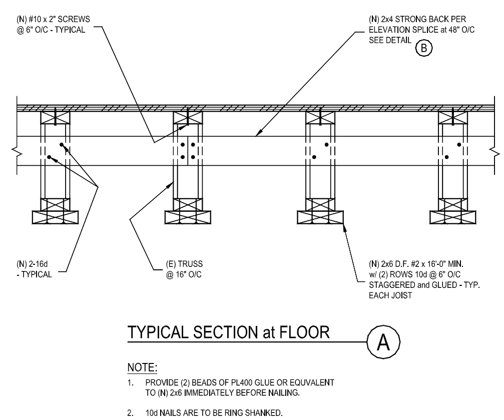

Figure 4 – Detail of Added Strongbacks

Also, double 2x4 strongback bridging was added at the span's quarter points to utilize multiple trusses for concentrated loads as shown in Figure 4.

The retrofit floor met the criterion for span to live load deflection ratio since the added members increased the stiffness of the trusses by 67%. The retrofit live load deflection was calculated to be L/1004.

The retrofit floor also met the point load deflection criterion. The deflection under a 1 kN (225 lb.) load at midspan was calculated to be 1.1 mm (0.041 in.) if only two joists were assumed to support the load. The addition of bridging at quarter points changed this assumption to four joists supporting the load. Thus, the deflection was 0.55 mm (0.021 in.). This change of assumptions was justified by the noting the similarities of this system to a studied condition comparing two rows of strong backs to a system without bridging. That study showed a 50% reduction in floor deflection under a concentrated 1 kN (225 lb.) load (Hu and Tardif, 2000).

The retrofit floor system did not meet the 15 Hz frequency criterion since its natural frequency with the added mass and stiffness of the retrofit material was calculated to be 14.3 Hz. However, for the system's span and estimated floor mass of approximately 0.475 kN/m^2 (10.0 $lb./ft.^2$), designing to meet a frequency of 15 Hz is equivalent to designing for a live load deflection criterion of L/1000 without adding the retrofit mass or L/1108 with the added retrofit mass.

Though not completely satisfied with the floor performance, the owners of these homes accepted the performance of the retrofitted floors.

CASE STUDY #2

The second case study also involves open web truss floor systems built into a number of single-family production residences. These floor systems support bedrooms and bathrooms with associated partitions. The area below these floors is somewhat open and has very few partitions. Additionally, the trusses in this floor system are parallel to the wall with the room entry as shown in Figures 5 and 7.

Many occupants complained of floor vibrations and swaying furniture in the master bedroom, particularly as they walked into the room from the hallway. The complaints focused on the swaying of the furniture located along the entry wall. As they walked into the room, any furniture that was against this wall visibly swayed and rattled or moved any decorative items placed in or on it. Because of the room layout, most occupants had an armoire or TV with picture frames on top at this location as shown in Figure 5. The homes that did not have furniture along this wall did not have complaints about the floor.

The truss depth for this floor system is 356 mm (14 in.) and the span is 6.70 m (22 ft.). The joists are spaced at 406 mm (16 in.) on center. The floor sheathing is 16 mm (0.625 in.) oriented strand board and the ceiling consists of one layer of 12 mm (0.5 in.) gypsum board.

We investigated five homes, and the floors were tested using a frequency controlled oscillating mass and accelerometers connected to the floor. The results of these tests showed first natural frequencies varied between 15.5 Hz and 17.2 Hz as shown in Figure 6. The testing also produced varied results for higher frequencies that appeared to be more related to the placement of furniture at the time of testing.

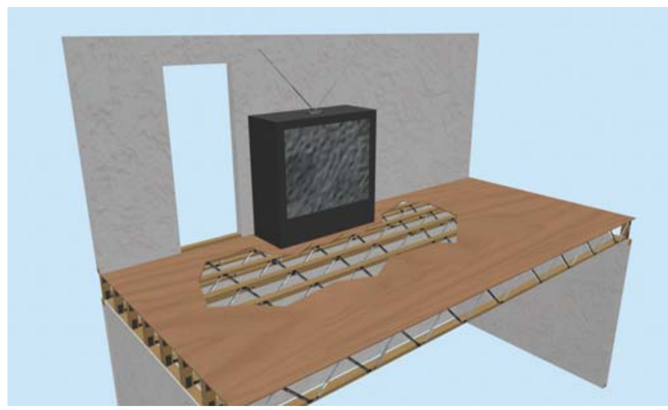

Figure 5 – Furniture Placement Relative to Truss Layout.

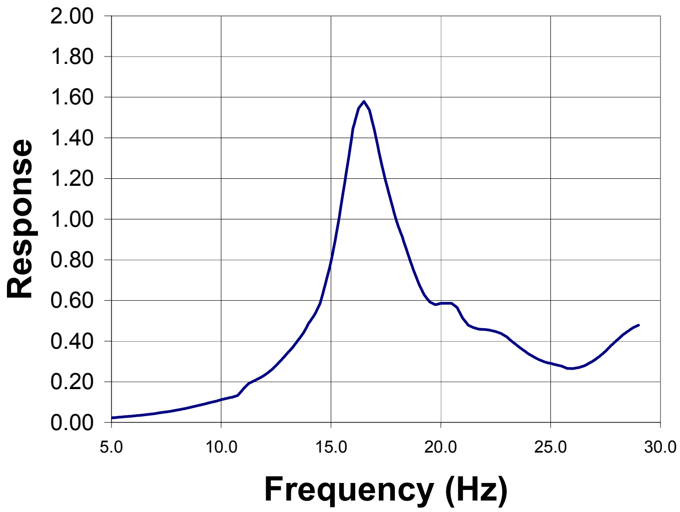

Figure 6 - Graph of Frequency Response from Random Excitation Shaker on Original Floor

In this case it appears that the serviceability performance of the floor was related more to a stiffness incompatibility between adjacent floor joists. When a piece of furniture rests partially on a stiff portion of the floor at a partition attachment and partially on a parallel floor joist free to deflect it can sway significantly under a person's heel drop.

The floor system did meet the span to live load deflection criterion with a computed deflection of 13.0 mm (0.51 inches) or L/517 for a 1.9 kN/m^2 (40 lb./ft.^{2}) live load.

However, it did not meet the 1kN (225 lb.) point load deflection criterion, which would have required a deflection of only 0.67mm (0.027 in.) for this span. The computed deflection at midspan for this point load is 2.0 mm (0.078 in.) assuming only two joists take the load or 1.0 mm (0.039 in.) assuming four joists share the load. If a piece of furniture placed along the entry wall is 1.22m (4 ft.) tall and one joist bay or about 406mm (16 in.) wide the differential deflection at the base will result in a lateral movement of the top of approximately 6 mm (0.25 in.). Movement slightly larger than this magnitude was noted in several homes.

With tested frequencies varying between 15.5 Hz and 17.2 Hz, this floor system met the 15 Hz natural frequency criterion by the results of the physical testing, but not by calculation. The theoretical first natural frequency was calculated to be 11.3 Hz. It is assumed that the presence of partitions on the floor changed the assumed stiffness and/or mass to produce a natural frequency far from the simple span with uniform mass assumption that was made for the theoretical calculated frequency.

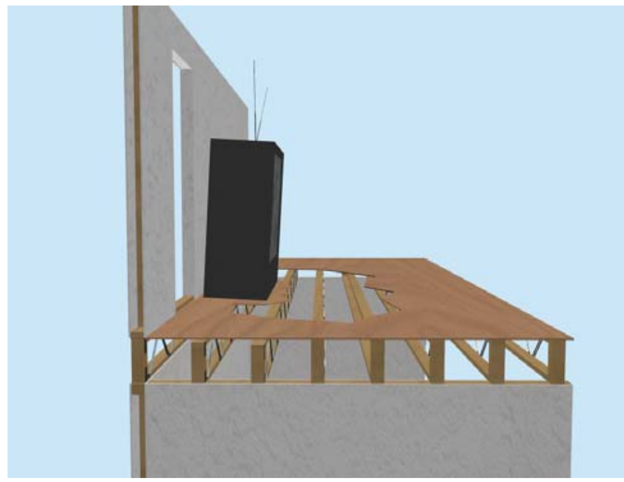

Figure 7 – Movement of Furniture with Joist Deflection.

In this case the entire floor system was not retrofitted since the complaints centered more on the furniture issue than the bounciness of the floor. Instead, a less expensive solution was chosen that consisted of anchoring the furniture near its top to the entry wall. In essence, this suspends the furniture from the partition so it does not sway as the joist adjacent to the wall deflects. Another solution for this issue could have been the installation of bridging to spread the load and equalize the deflection among adjacent floor joists.

CASE STUDY #3

The third case study involves a high end single family home whose floor system was constructed with Trus Joist oriented strand board web joists having engineered lumber flanges. This home had two areas of concern, both located on the second floor. One was in the master bedroom and consisted of a rattling noise heard when walking in the master bedroom and movement of furniture when entering the room. The other was the swaying of furniture placed adjacent to a wall dividing a second bedroom.

Upon a review of the plans it was noted that the master bedroom floor system consists of 302 mm (11.875 in.) deep oriented strand board web joists at 406 mm (16 in.) on center, spanning 5.64 m (18.5 ft.). No bridging was specified for the floor joists. The floor sheathing is 19 mm (0.75 in.) oriented strand board and the ceiling below is directly applied 12 mm (0.5 in.) gypsum board. The trusses were designed for a live load of 1.9 kN/m^2 (40 $lb./ft.^2$).

No physical vibration tests were performed on this floor. A comparison to the serviceability criteria is noted below.

The calculated live load deflection for the system is L/533, which exceeds the span to live load deflection criterion.

The point load criterion requires that the midspan deflection for a 1 kN (225 lb.) point load placed at the midspan of these joists be 0.86 mm (.034 in.). The calculated deflection for this point load is 1.89 mm (0.075 in.) assuming only two joists take the load or 0.90 mm (0.037 in.) assuming four joists share the load.

The first natural frequency was calculated to be 12.9 Hz based on an estimated system weight of 0.35 kN/m^2 (7.3 $lb./ft.^2$). The system therefore does not meet the 15 Hz frequency criteria.

Joist information was also entered into the TJ Beam 6.02 program to determine the TJPro Ratings. The rating was reported as 38, this corresponds to approximately 70% of the population finding the floor assembly acceptable.

Our observations indicated that the rattling noise was coming from a large double paned window that had a false mullion between the glass sheets. Vibrations caused by walking on the floor were being transmitted to the window and causing its vibration. Interestingly, the other windows in the house had rubber isolators on the mullions preventing this rattling. However, this window was missing the isolator and the resulting vibration caused a noticeable rattling. The furniture movement was caused by the same framing configuration as shown in Case #2. In this case the furniture was armoire that was approximately eight feet tall and two feet wide.

The second bedroom has a partition supported by and parallel to the floor joists dividing it from the third bedroom. The owner was concerned only with the second bedroom, not the third, even though the framing configurations were almost identical. The second bedroom had a chest of drawers with picture frames on the top located against the dividing wall. As the owners walked near the chest the frames would visually and audibly vibrate. The third bedroom had a smaller chest of drawers against the wall, but it had no sensitive decorations on top. As a test, a picture frame was moved from the second bedroom to the third and the floor that was previously not a concern became unacceptable.

The second bedroom had the same floor system as the master bedroom although the span was slightly shorter at 5.33 m (17.5 ft.). It met the span to live load deflection criterion because its calculated live load deflection was L/625. The point load deflection criterion specifies a 0.91mm (0.036 in.) deflection for these joists. Their calculated deflections are 1.6 mm (0.063 in.) for two joists effective and 0.8 mm (0.032 in.) for four joists effective. Therefore, the joists meet the point load criterion with four joists effective. Also, the system's natural frequency was calculated to be 14.4 Hz. Finally, as with the master bedroom joists, floor system information was entered into the TJ Beam 6.02 program and a 42 rating was reported. This corresponds to 75% of the population finding the floor assembly acceptable.

Similar to case study #2, the floor systems in the bedrooms appeared to have a problem with incompatibility of adjacent floor joists.

The solutions for this case study was to replace the window in the master bedroom and add bridging at quarter points between the joists that are parallel to the partition to minimize the incompatibility of adjacent floor joists.

Conclusions

These three case studies demonstrate that although floor serviceability is subjective, available floor serviceability criteria do provide reasonable guidance to minimize serviceability problems in long span engineered wood floor systems.

The application of serviceability performance criteria in these case studies reveals that certain proposed criterion are more indicative of actual performance than others. The floor spans involved in these case studies ranged from 5.33 to 6.70 m (17.5 ft. to 22 ft.). The floor system weights ranged from 0.37 kN/m^2 to 0.475 kN/m^2 (7.3 lb./ft.^{2} to 10.0 lb./ft.^{2}). The live load deflections ranged from L/517 to L/1004. Accordingly, the calculated first natural frequencies were between 11.3 to 14.5 Hz.

The span to live load deflection criterion is the most commonly used criterion in current design. This criterion may work in most cases, however, as was shown in these three case studies is not the best indicator of floor performance. All three case studies involved floors that met the L/480 live load deflection criterion, yet several were shown to be unacceptable to their occupants. However, it is unfair to categorize this criterion as ineffective since the cases chosen were not random, but rather were problematic designs to begin with.

The best indicator of floor performance for these case studies appears to be the performance criterion in the National Building Code of Canada, Part 9, as modified in 1997 for engineered wood products. By placing different limits on different joist span's deflection under a concentrated load, this criterion is able to capture several behavior problems. This criterion can also help to minimize the issue of stiffness incompatibility between adjacent floor joists. To practically meet this criterion for light framed floors the joists must have a significant cross span stiffness to allow distribution of the point load to multiple joists. This cross span stiffness and the limit of absolute deflection under a load similar to a heal drop would seem to minimize the issue of furniture spanning over floor joists with incompatible deflection behavior. This bridging or increase in cross span stiffness also appears to be the least expensive way of increasing the floor serviceability performance.

The natural frequency criterion does not appear to be well suited for the weights and span of the floors involved in these case studies. Given a certain floor system weight the natural frequency criterion can be directly converted into a live load deflection to span ratio for a given live load. For the weight of the floor systems in these case studies, which are common in residential construction, the equivalent live load deflection to span ratio requirements are L/800 to L/1000 for 1.9 kN/m^2 (40 lb./ft.^{2}) live loads. Although the floors with such criteria would most likely perform well, this criteria would seem to be too restrictive for many cases.

Finally, the manufacturer specific rating system appears to provide some beneficial guidance during the design process and alert designers to systems that may be problematic.

To compare the different serviceability criterion for residential floors Figure 8 was developed. The figure is only valid for a floor with an actual dead load of 0.38 kN/m^2 (8 lb./ft^2), a live load of 1.9 kN/m^2 (40 lb./ft.^{2}), and an assumption of cross span stiffness capable of sharing a 1kN (225 lb.) load over 4 joists spaced 406 mm (16 in.) on center. The comparison indicates that for longer span timber residential floors, span to live load deflection criterion may need to increase with longer joist spans.

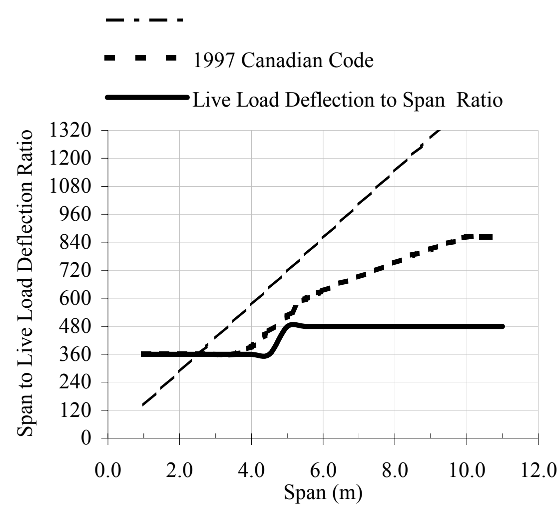

Figure 8: Serviceability Criteria Normalized to Span to Live Load Deflection Ratio

Finally, the case studies show that deflection incompatibilities can actually alert building occupants to deflections that may otherwise have not been problematic. The study of multiple tract homes with identical framing designs, varied performance measurements and varied owner sensitivity to serviceability issues demonstrate that there is more to serviceability than a design criteria. The serviceability issues in these three case studies can be separated into two categories. The first is the traditional serviceability issue of a "bouncy" floor, the second is a localized issue of deflection incompatibility between adjacent floor joists. These two categories are related to one another in that a localized incompatibility can sensitize an occupant to the bounciness of a floor system. Once people become sensitized by visible movements of furnishings or decorative items placed on these furnishings, the floor system is viewed as problematic and it can be very difficult to desensitize occupants through remedial modification of the system.

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