



Research Report

Special Floor Loading Considerations in Typical Residential Construction

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Introduction:

The design of a typical residential flooring system is usually a simple process: estimate the appropriate dead loads based on floor surface and subfloor materials, select the appropriate live load based on the intended purpose of the room, and then design the floor trusses composed of the necessary material and required spacing to support the given loads at a particular span. If designing with engineered wood products (EWP), one would simply select the required joist size and spacing from established tables. The simplicity of this approach originates from the fact that loads are unpredictable. It is impossible to determine how a particular room will be used or what loads it will be subjected to and where those loads will be located, so it is simply assumed that a uniform load is distributed over the entire floor surface. This approach is very simple and, although it works and is even conservative a majority of the time, it does not account for every situation.

This report will explore some special floor loading issues that are not specifically mentioned in the building codes and require special attention to ensure that the floor system is properly designed with no serviceability issues. The following are the major issues that will be discussed:

Stone/Ceramic Tiles – The use of brittle flooring surfaces such as stone, ceramic, or glass tiles require more strict deflection limits than the building codes suggest.

Large Concentrated Loads – Loads from sources such as aquariums, fireplaces, and granite countertops can be large and require consideration beyond the standard floor truss design.

Floor Vibrations – Although usually not a structural issue, vibrations caused by typical service conditions can be annoying to homeowner/occupants and can be reduced or eliminated by stiffening the floor system.

Key Definitions:

SERVICEABILITY – A state in which the function of a structure, its appearance, maintainability, durability and comfort of its homeowner/occupants are preserved under normal usage. This refers to, among other things, a structure that does not deflect or otherwise deform in a manner that suggests it is unsafe to its homeowner/occupants.

UNIFORM LOAD – A distributed load or pressure which is applied to an area (typically given in units of pounds per square foot [psf]).

DEAD LOAD – The weight of materials of construction incorporated into the building, including but not limited to walls, floors, roofs, ceilings, stairways, built-in partitions, finishes, cladding and other similarly incorporated architectural and structural items, and the weight of fixed service equipment, such as cranes, plumbing stacks and risers, electrical feeders, heating, ventilating and air conditioning systems and automatic sprinkler systems.

LIVE LOAD – A load produced by the use and occupancy of the building or other structure that does not include construction or environmental loads such as wind load, snow load, rain load, earthquake load, flood load or dead load.

NATURAL FREQUENCY – The frequency at which a system oscillates when not subjected to a continuous or repeated external force.

LONG TERM DEFLECTION – Vertical deflection caused by the continuous presence of load over an extended period of time. Long term deflection in wood members is caused by a phenomenon known as “creep”.

CREEP – Also known as “plastic flow”, creep is the act of permanent shortening under long term, continuous compressive stress. Wood members are susceptible to creep especially in long span members, members carrying substantial dead loads, and members that are subjected to large amounts of temperature and moisture change during their service life.

Background:

Serviceability

In the design of any inhabited structure there are two main design goals that must be achieved. First, and most important, the structure must be strong enough to support all of the loads it is designed to carry. Second, the structure must be “serviceable” or rigid enough that deflections, vibrations and other deformations are not noticeable to its homeowner/occupants, and do not adversely affect any non-structural building components. The International Building Code (*IBC*) describes strength and serviceability limit states as the conditions beyond which a structure is considered unsafe and not useful respectively. The strength aspect of design is typically the focus of engineers and designers (as it should be) since any errors in strength design could result in damage or collapse of the structure, which can be costly both monetarily and from a human safety standpoint. Serviceability, on the other hand, typically does not receive the same level of attention because the stakes are not as high.

The International Residential Code (*IRC*) has never provided a specific limit state for serviceability but it does provide guidance on serviceability in the form of live load deflection limits for various structural members (see [Table 1](#)) where “L” is the floor truss (or EWP) span in inches.

STRUCTURAL MEMBER	ALLOWABLE DEFLECTION
Rafters having slopes greater than 3:12 with no finished ceiling attached to rafters	<i>L/180</i>
Interior walls and partitions	<i>H/180</i>
Floors/ceilings with plaster or stucco finish	<i>L/360</i>
All other structural members	<i>L/240</i>
Exterior walls—wind loads ^a with plaster or stucco finish	<i>H/360</i>
Exterior walls with other brittle finishes	<i>H/240</i>
Exterior walls with flexible finishes	<i>H/120^d</i>
Lintels supporting masonry veneer walls ^e	<i>L/600</i>

Table 1: Allowable Deflection of Structural Members Under Live Load¹

Similarly, the *IBC* code provides a table for deflection limits (see [Table 2](#)). This guidance, however, is fairly general and fails to capture specific serviceability related design conditions in many cases.

¹ [2012 IRC Section R301.7](#)

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CONSTRUCTION	<i>L</i>	<i>S</i> or <i>W^f</i>	<i>D + L^d, g</i>
Roof members: ^e			
Supporting plaster or stucco ceiling	//360	//360	//240
Supporting nonplaster ceiling	//240	//240	//180
Not supporting ceiling	//180	//180	//120
Floor members	//360	—	//240
Exterior walls and interior partitions:			
With plaster or stucco finishes	—	//360	—
With other brittle finishes	—	//240	—
With flexible finishes	—	//120	—
Farm buildings	—	—	//180
Greenhouses	—	—	//120

Table 2: Deflection Limits²

The *National Design Specification® (NDS®) for Wood Construction* provides no serviceability limits or guidance. It does state that the deflection of wood members needs to be considered in design, however, no deflection limits are provided. The lack of more specific serviceability requirements leaves room for interpretation. The purpose of this report is to provide an industry position on designing floor trusses to better account for some of these special floor loading issues. [Appendix A](#) provides an example comparing the differences between a code compliant floor truss design with another that took granite countertops into the design considerations.

Analysis:

Stone/Ceramic Tile

Stone and ceramic tiles are a popular flooring material due to its versatility, long life cycle and low maintenance; however, certain problems arise if the tiling is not properly installed or if not enough consideration is given in the design of the supporting floor system. Since stone, ceramic and glass are brittle materials, they are more susceptible to cracking as a result of floor deflection. The tile industry has known for some time that the standard L/360 maximum live load and L/240 maximum total load deflection limits provided by the building code are not adequate to prevent the cracking of tiles.

For this reason, industry leaders such as the Tile Council of North America (TCNA) and the Marble Institute of America (MIA) suggest in their standards to use a stricter total load deflection limit of L/720 where stone tiles are used.

MIA Installation/General Information 3.8.3 Frame Construction. The subfloor areas over which stone tile is to be applied must be designed to have a deflection not exceeding L/720 of the span. In calculating load, the weight of the stone and setting bed must be considered.³

3.8.3.1 Strongbacks, cross-bridging or other reinforcement shall be used to limit differential deflection between adjacent framing members.

TCNA provides a response to the question: “What is the acceptable deflection for a floor that will be tiled?”⁴

Traditionally, the accepted minimum requirement for floor rigidity is L/360 - before the tile underlayment is installed. The L/360 standard means that the floor should not deflect more than the "span" divided by 360. If the span of the joists is 10 feet (between supports), then the deflection should not be more than 1/3" between the center and the end. Frequently, there is misunderstanding regarding deflection between joists. For example, while joist manufacturers regularly meet the standard L/360 criteria for code construction with 24" o.c. (on center) systems, these floors often have deflection between the joists exceeding L/360.

Recent research has shown tile to fail, under some conditions, when the floor is more rigid than L/360. In fact, failures at L/600 have been observed. It is for this reason that recommendations for floor rigidity are not based on deflection measurements but on empirically established methods found to work over normal code construction.

² [2012 IBC Section 1604.3](#)

³ [Marble Institute of America, Installation/General Information, 2011](#)

⁴ www.tcnatile.com/faqs/30-deflection.html

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The *National Design Standard for Metal Plate Connected Wood Trusses, ANSI/TPI 1-2014* states certain floor coverings require more restrictive deflection criteria than the deflection limits provided in Table 7.6-1.

ANSI/TPI 1 Table 7.6-1 Footnote 2: For ceramic tile, Truss spacing and appropriate dead load for the installation method, and other aspects of design per ANSI A108/A118/A136 shall be such that the system passes the requirements of the Building Designer per Chapter 2 of this standard (ANSI/TPI 1).

Earlier editions of *ANSI/TPI 1* explicitly referenced a 16-inch on center spacing limit for some floor coverings. But now *ANSI/TPI 1* just references *ANSI A108/A118/A136* for truss spacing since there are a number of available systems that allow 19.2- and 24-inch on center spacing of supporting trusses.

The *American National Standard Specifications for Installation of Ceramic Tile ANSI A108* states total load deflection (not the code minimum total load deflection of L/240) criterion should be L/360:

ANSI A108 Section AN-2.3 Deflection. Floor areas over which tile is directly bonded to subfloor shall not have a deflection greater than L/360 of the span when tested per ASTM C627. Make allowances for live load and impact as well as all dead load, including weight of tile and setting bed.

NOTE: Stone tile installations may require a more rigid substrate. Refer to MIA recommendations.

It is easy to overlook this added restriction in the design phase because it is not in the building code and, therefore, may not be common knowledge.

Designing with stone or ceramic tile (when done appropriately) will require special consideration in the design phase. A lower deflection limit means stiffness of the floor trusses will need to be greater than the minimums specified by the building code. Trusses may need to be deeper (see Floor Vibration discussion [Table 3](#)), higher grade or spaced closer together to meet the deflection requirement. In addition, considerations should be given to stiffening the subfloor in areas where brittle tiles are used. This will help prevent issues with differential settlement between trusses as well as localized, inter-panel deflections along the top chords of floor trusses. As important as overall deflection is in designing a floor system, it can be just as important to pay attention to localized deflections either between trusses or within a single panel of a truss.

It is also important that the design of the trusses considers the added weight imposed by the tile flooring. The dead load from a typical stone tile (with subfloor) can be as high as 20 psf, which is considerably higher than the dead load from other common flooring surfaces. The extra dead load requires further consideration since it will increase the amount of long term deflection in the floor system. In general, the provisional deflection criteria set by the *IRC/IBC* and its referenced standards are a short-term criteria.

ANSI/TPI 1-2014 Section 7.6 provides guidance on how to predict time dependent deformation under long term loading:

ANSI/TPI 1 Section 7.6 DEFLECTION

7.6.1 Method of Calculation.

... Deflection due to live load (Δ_{LL}) shall be based on the live load, deflection due to dead load (Δ_{DL}) shall be based on the dead load, and deflection due to total load (Δ_{TL}) shall be based on the full load including both dead and live loads, for each load case. Time dependent deformation under long term loading shall be determined as follows, except for purposes of deflection limitation in accordance with the International Building Code as noted in the next paragraph.

$$\Delta_{LongTerm} = K_{Cr} \times \Delta_{LT} + \Delta_{ST}$$

where:

K_{Cr} = Creep factor

≥ 2.0 for trusses using seasoned lumber used in dry service conditions

≥ 3.0 for trusses using green lumber or for wet service conditions

$\Delta_{LongTerm}$ = Total Long Term Deflection due to immediate deflection of both short-term and long-term loads and creep deflection of long-term loads

Δ_{LT} = Immediate deflection due to the long term component of the design load (immediate deflection due to the portion of load considered to be present over a sustained time period, typically dead load or a portion of dead load)

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Δ_{ST} = deflection due to short term or normal component of the design load (deflection due to transient loads, typically live load)

For purposes of deflection limitations in accordance with the International Building Code, trusses using only seasoned lumber used in dry service conditions shall determine the deflection for the total load check as follows.

$$\begin{aligned}\Delta_{CR} &= \text{Deflection due to Live Load plus Creep Component of Deflection due to Dead Load} \\ &= \Delta_{LL} + (K_{CR}-1) \times \Delta_{DL}\end{aligned}$$

It should be noted, excessive deflection in the flooring structure is not the only reason cracking occurs in brittle type tiles. Cracking in tiles can also be caused by an uneven subfloor surface, bearing height differentials or improper installation techniques for either the subfloor or the tile itself.

Heavy Concentrated Loads

As previously mentioned, wood floor truss systems are commonly designed to carry a uniformly distributed load comprised of dead and live load components. The floor truss system is designed assuming this uniform load is applied over the entire floor area. In a typical residential structure, an estimated dead load of approximately 10 psf might be used along with a live load of 40 psf depending on the type of room and the building materials used.

Since, in reality, an entire floor area is never simultaneously loaded, this approach is usually conservative, which is unavoidable given the uncertainty of the live loads the floor will actually be subjected to. The uniform load approach to design, however, is not adequate in determining whether a floor system can support heavy concentrated loads such as those from aquariums, storage systems and heavy granite countertops. The building design drawings should always be checked to make sure any heavy concentrated loads are identified and accounted for in the floor design.

It is important loads such as these be considered in conjunction with the uniform design loads. It is rarely possible to anticipate loads such as these and it is consequently very hard to deal with them in the design phase. For certain non-residential structures, the *IBC* specifies a minimum concentrated load that must be considered at any point on the floor of the structure. There is, however, no minimum concentrated load required for residential buildings. Even though it is not required, it can be beneficial to consider a moveable concentrated load at critical locations on a structure's floor plan. A 300 lb. load acting over an area of 2" x 2" is a good suggestion since it is the same requirement given by the *IBC* for stairways and exits in one and two family dwelling. The 300 lb. load need not be considered to act concurrently with the uniform live load. The use of a minimum concentrated live load in floor design can provide peace of mind and the ability to add extra loads to a floor system (within the limits of the design load). Whenever a heavy concentrated load is encountered, the floor truss system's structural integrity should be re-evaluated.

A floor's adequacy to carry added concentrated loads tends to be case specific, however. In the absence of a concentrated live load being considered in the initial design, there are several general tips that can be used:

- Try to place concentrated loads over or near underlying columns or bearing walls. Remember that not all walls are bearing walls, so be sure to check.
- Position concentrated loads such that they are carried by multiple floor trusses.
- Add concentrated loads to smaller rooms that have shorter, stiffer trusses (assuming trusses are the same size and spacing throughout the structure).
- Use proper strong backs and bridging between trusses to increase interconnectivity and help distribute load more effectively.

Floor Vibration

Vibration in residential buildings has not historically been an issue because floor spans have typically been relatively short. With advances in building components and structural design methods, however, floors are able to span greater distances, which makes them more flexible and susceptible to vibrations. Vibrations in a flooring system can be caused by something as simple as pedestrian foot traffic and can be annoying to a building's inhabitants. Dealing with building vibration is a difficult task since there is no guidance provided in the building codes. Furthermore, the negative effects or vibration are often not structural and are very subjective. What one person considers to be an annoying level of vibration might be completely unnoticeable to someone else.

Studies have shown that humans are the most sensitive to vibrations with frequencies between 4 and 10 Hz. A floor system with a natural frequency that falls in this range is therefore considered undesirable since it is most susceptible to

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vibrations within the human sensitivity range. The natural frequency of a beam member (such as a floor truss) has a direct relationship with the beam's flexural stiffness. A stiffer floor system will have a higher natural frequency and vibrations through that system will likely go unnoticed by its inhabitants.

Floor systems that meet building code requirements for serviceability are not immune from vibration issues. Vibration issues are especially prevalent in "sleeping rooms", which can be designed using a uniform live load of 30 psf as opposed to 40 psf in most other rooms in a residential structure. Rooms originally designed to be sleeping rooms are often repurposed and used as playrooms, offices or home exercise spaces, all of which will see much more human activity than the design intended. The combination of a reduced design live load and a deflection criteria of L/360 allows the floor trusses to be relatively shallow and flexible especially at longer spans and where close truss spacing is used. As previously discussed, a floor system with flexible trusses will have a low natural frequency and will invite unwanted vibrations. Herein lies the common source of the problem.

Most designers use a floor span-to-depth limitation ($L/d = \text{span in inches} / \text{depth in inches}$) of 20 to prevent objectionable floor vibration. Designing a floor to a higher deflection ratio does not guarantee acceptable performance for all, but typically an L/d ratio of 16 provides minimal vibration. [Table 3](#) provides span-to-depth limitations based on these ratios.

Depth	L/d 16	L/d 20
12"	16'-0"	20'-0"
14"	18'-8"	23'-4"
16"	21'-4"	26'-8"
18"	24'-0"	30'-0"
20"	26'-8"	33'-4"
22"	29'-4"	36'-8"
24"	32'-0"	40'-0"

Table 3: Floor Truss Span-to-Depth Limitations

The easiest method to reduce vibration risks, then, is to increase the deflection criteria used in the floor design. Doing so will consequently increase the stiffness of the floor system. This should be done especially when dealing with longer truss spans. Designing a floor system that is stiffer than the minimum allowed by the building code will serve to eliminate or at least reduce most annoying vibrations.

Another practice to reduce vibration is to more securely attach floor sheathing to the floor system. Glue in combination with screws will yield the greatest results. Using more robust connections will improve the performance of the floor diaphragm and will help distribute localized forces to neighboring floor trusses. Attaching strongback bracing as recommended on floor trusses will also reduce floor vibrations. See [Figure 1](#) for standard industry strongback detail.⁵

⁵ <http://support.sbcindustry.com/structuraldetails.php>

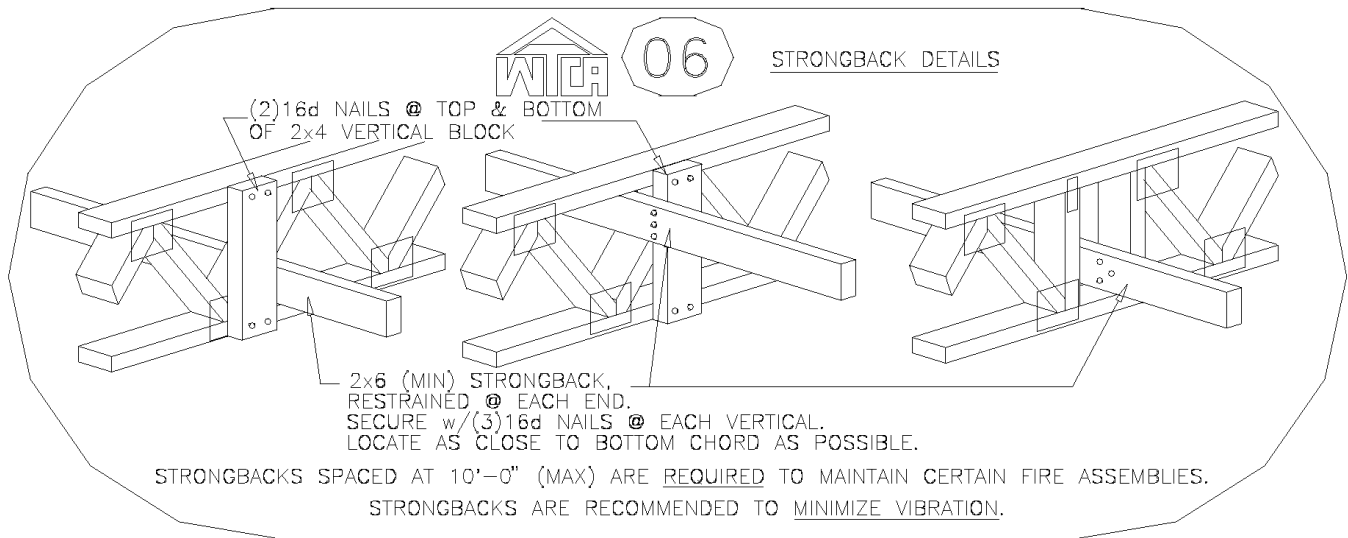


Figure 1: Strongback Detail

Conclusion:

It is clear from the discussions above that several special floor loading issues can be solved by designing a floor system to be slightly above and beyond the minimums required by the building code. What follows are industry recommendations to address special floor loading to increase floor system stiffness and limit deflections. In all cases, SBCA recommends gluing the underlayment to the subfloor and fastening with screws rather than nails in addition to the installation of strongbacks. The Building Designer should establish what deflection, load and on-center spacing requirements apply to any particular floor covering at the time of design. All parties in the design process should keep in mind as truss spans and material weight increase (i.e., marble or stone tile), the greater the risk for serviceability and performance issues. If no building design information is given, Truss Designers should not assume live load deflection criteria of L/360. Rather, get the information from the Building Designer in writing so the trusses are designed stiff enough to limit deflections, vibrations and any other deformations to acceptable levels for the homeowner/occupants.

Ceramic Tile: It is suggested that floor trusses be designed for both a live load and total load deflection of L/360 to account for floors that have ceramic tile flooring (or may be converted to in the future). Additional load should also be added to the top chord dead load of the floor trusses according to the weights provided by the ceramic tile manufacturer. If unknown, an additional 7 psf is suggested for ceramic tile flooring.

Stone Tile: It is suggested that floor trusses be designed for a total load deflection of L/720 to account for floors that have stone tile flooring (or may be converted to in the future). Additional load should also be added to the top chord dead load of the floor trusses according to the weights provided by the stone tile manufacturer. Due to the wide range of stone tiles available, no suggested load is provided.

Granite Countertops: Unless otherwise specified as to the exact location of kitchen islands with granite countertops, it is suggested that an additional 20 psf dead load be added to the top chord floor truss design to account for kitchen islands with up to 2 inches of granite.

APPENDIX A: Example Design

Consider a kitchen area in which stone floor tiles will be used. In addition, a 4' wide island with a granite countertop will be installed in the center of the floor span. The assumptions for this example are as follows:

- Floor trusses are 18" deep with SPF No. 2 2x4 top and bottom chords spaced at 24" on center.
- Floor truss span is 22'
- Dead load from stone tile floor (including subfloor) is 20 psf
- Floor live load is 40 psf (per *IBC* and *IRC* codes)
- Granite topped island acts as a 200 lb. concentrated load (per truss) at the center of the span
- Floor trusses are analyzed as being simply supported beams
- Critical load combination = 1.0D + 1.0L

The resulting deflections for this condition are calculated below in which the first term is the deflection from the uniform dead and live loads, and the second term is the deflection from the concentrated midspan load from the island. (Simplified beam deflection calculations are used for this example):

$$\frac{5(120 \text{ lbf}/\text{ft})(\frac{1\text{ft}}{12\text{in}})(264\text{in})^4}{384(1,400,000 \text{ lbf}/\text{in}^2)(716.6\text{in}^4)} + \frac{200\text{lbf}(264\text{in})^3}{48(1,400,000 \text{ lbf}/\text{in}^2)(716.6\text{in}^4)} = 0.707\text{in}$$

The standard deflection limit of L/360, which is equal to 0.733" (264/360) in this case, is satisfied; however, the recommended limit of L/720 for floors supporting stone flooring tiles, which equates to 0.367" (264/720), is substantially exceeded. This could lead to cracking in the tiles and the floor system should therefore be made stiffer to eliminate some of the deflection.

Some common options to stiffen a floor system include:

- Increasing the depth of the floor truss
- Selecting a wood grade (specifically for the truss chords) with a higher modulus of elasticity (E)
- Reducing the truss spacing
- Reducing span (typically not an option)

A solution could be to increase the truss depth to 21", use SP No. 1 2x4 chords, which have a greater modulus of elasticity, and reduce the joist spacing to 19.2" on-center. Doing so yields the following deflection:

$$\frac{5(96 \text{ lbf}/\text{ft})(\frac{1\text{ft}}{12\text{in}})(264\text{in})^4}{384(1,700,000 \text{ lbf}/\text{in}^2)(1000.1\text{in}^4)} + \frac{200\text{lbf} \frac{19.2}{24}(264\text{in})^3}{48(1,700,000 \text{ lbf}/\text{in}^2)(1000.1\text{in}^4)} = 0.334\text{in}$$

With the modifications to the design, the deflection meets the stricter requirements for tile flooring. The modified design is further beneficial because the narrower truss spacing will result in less deflection between trusses and will allow forces to be distributed between trusses more efficiently.

In order to determine whether or not vibration is a potential issue, we can use a rule of thumb proposed in the publication, "Serviceability of Floor Systems in Existing Residential Timber Frame Structures" by Castle and Pomerleau⁶, in which the equations for calculating the natural frequency and deflection of a beam are combined to output a deflection value below which vibration should not be an issue. According to this approach, a beam of any length having a dead load deflection below 0.055" will have a natural frequency that is greater than 15 Hz and places it outside of the range of human sensitivity.

In the example above, the dead load deflection for both scenarios is greater than 0.055" threshold, which means the natural frequency of the truss is within range of human sensitivity and the floor system could be susceptible to vibration issues. This criteria is more restrictive for longer spans than other criteria.

⁶ www.fwcse.com/wp-content/themes/FWC/Publications/Floor.pdf