Special Floor Loading Considerations in Typical Residential Construction

Overview

Revised 3/24/2017

SBCA

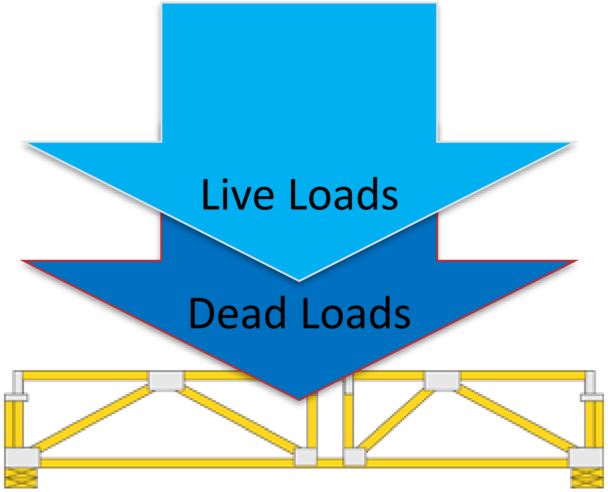
SBCA has been the voice of the structural building components industry since 1983, providing educational programs and technical information, disseminating industry news, and facilitating networking opportunities for manufacturers of roof trusses, wall panels and floor trusses. **SBCA** endeavors to expand component manufacturers' market share and enhance the professionalism of the component manufacturing industry.

Introduction

- There are several floor loading issues that are not specifically addressed in the building codes that require special attention by designers to avoid serviceability issues with the floor system.
- The lack of more specific serviceability requirements in the codes leaves room for interpretation.
- This presentation will provide an industry position on designing floor trusses to better account for special floor loading issues.

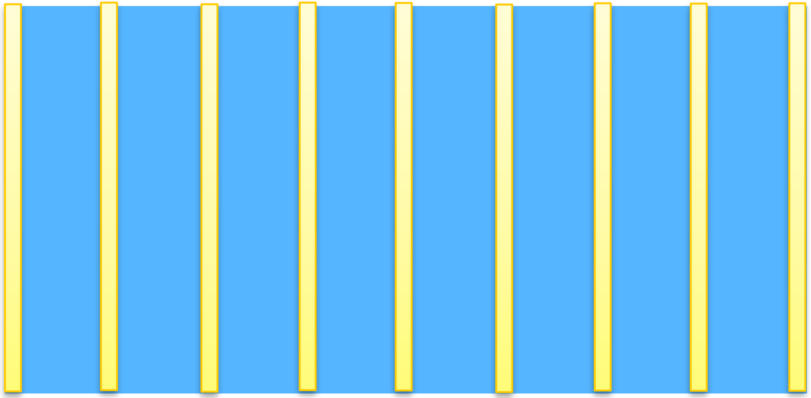
Introduction

- Residential floor design is usually very simple:
  - Estimate dead loads based on floor and subfloor materials
  - Select live loads based on the intended purpose of the room
  - Design the floor trusses or engineered wood products (EWP) to support the given loads at a particular span and spacing



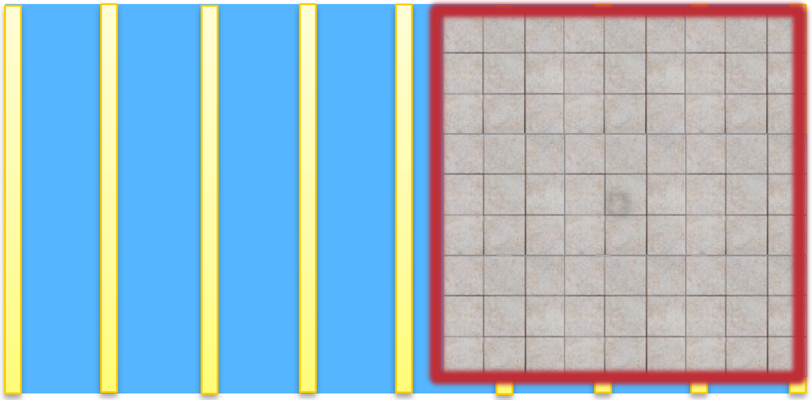
Introduction

- Because loads are unpredictable, it is simply assumed that a uniform load is distributed over the entire floor surface.
- Although this simple approach is conservative the majority of the time, it does not account for every situation, such as:



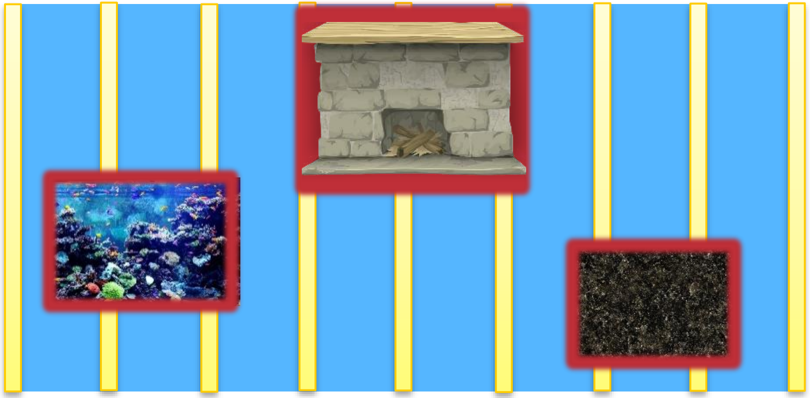
Introduction

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



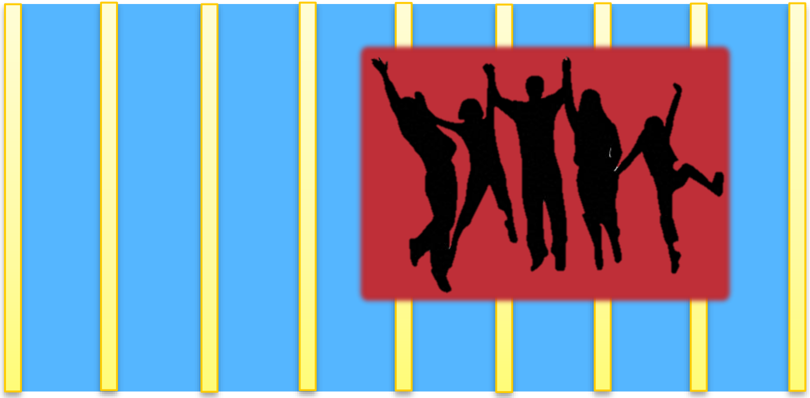
Introduction

- <u>Large Concentrated Loads</u>
  - Loads from sources such as aquariums, fireplaces, and granite countertops can be large and require consideration beyond the standard floor truss design load.



Introduction

- <u>Floor Vibrations</u>
  - Although usually not a structural issue, vibrations caused by typical service conditions can be annoying to homeowner/occupants and can be reduced 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.
- **UNIFORM LOAD**
  - A distributed load or pressure 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.

Key Definitions

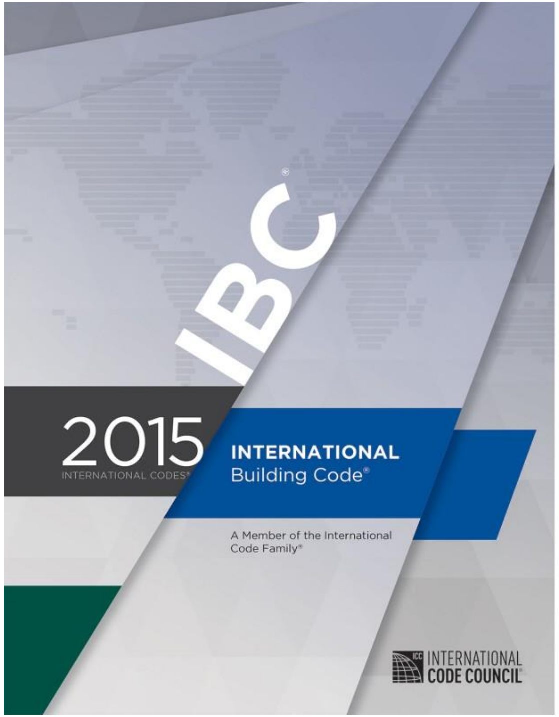
- **LIVE LOAD**
  - A load produced by the use and occupancy of the building or other structure that does not include construction or environmental loads such as wind load, snow load, rain load, earthquake load, flood load or dead load.
- **NATURAL FREQUENCY**
  - The frequency at which a system oscillates 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

- There are two main principles in the design of any structure:
  - Strength
    - The structure must be strong enough to support the loads it is designed to carry.
  - Serviceability
    - The structure must be "serviceable" or rigid enough that deflections, vibrations and other deformations are not noticeable, and do not adversely affect any non-structural building components.

Background

- 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.



Background

- 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.
- Serviceability, on the other hand, typically does not receive the same level of attention because the stakes are not as high.

Background

- The International Residential Code (*IRC*)
  - Has never provided a specific limit state for serviceability
  - It does provide live load deflection limits for various structural members

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

"L" is the floor structural member span in inches

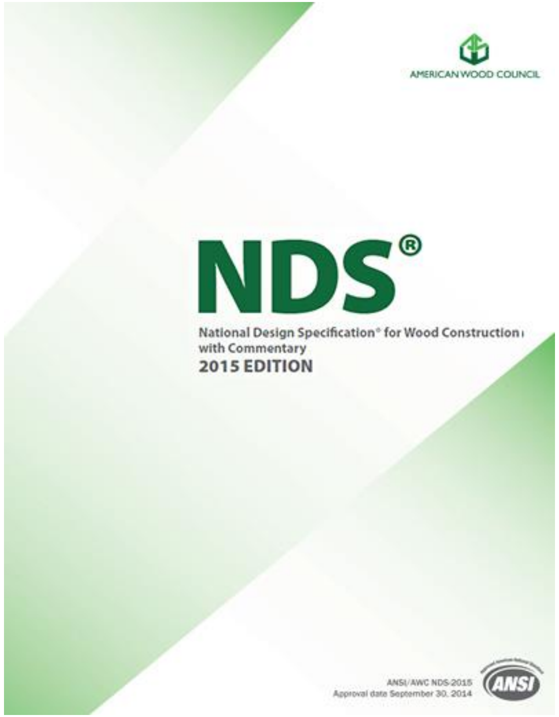
Background

- The *IBC*
  - Provides a table for deflection limits
  - However, this guidance is fairly general and fails to capture specific serviceability related design conditions in many cases

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

Background

- *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.



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.

Analysis – Stone/Ceramic Tile

- 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.

Analysis – Stone/Ceramic Tile

- 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.

Analysis – Stone/Ceramic Tile

- TCNA provides a response to the question: "What is the acceptable deflection for a floor that will be tiled?"
  - 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.

Analysis – Stone/Ceramic Tile

- 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).

Analysis – Stone/Ceramic Tile

- Earlier editions of *ANSI/TPI 1* explicitly referenced a 16-inch o.c. spacing limit for some floor coverings.
- 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" o.c. spacing of supporting trusses.

Analysis – Stone/Ceramic Tile

- The American National Standard Specifications for Installation of Ceramic Tile ANSI A108 states total load deflection 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.

Analysis – Stone/Ceramic Tile

- Designing with stone or ceramic tile requires consideration of deflection requirements in the design phase which may not be common knowledge, as they are not found in the building code.
- Trusses may need to be deeper, higher grade, or spaced closer together.

Analysis – Stone/Ceramic Tile

- While overall deflection is important, minimizing localized deflections can be crucial to performance.
- Stiffening the subfloor in areas where brittle tiles are used will help prevent issues with differential settlement either between trusses or within a single panel of a truss.

Analysis – Stone/Ceramic Tile

- The design of the trusses must consider the added weight of tile flooring.
- The dead load from a typical stone tile (with subfloor) can be as high as 20 psf, which will increase the long term deflection in the floor system compared to a typical floor having only 5 to 10 psf dead load.

Analysis – Stone/Ceramic Tile

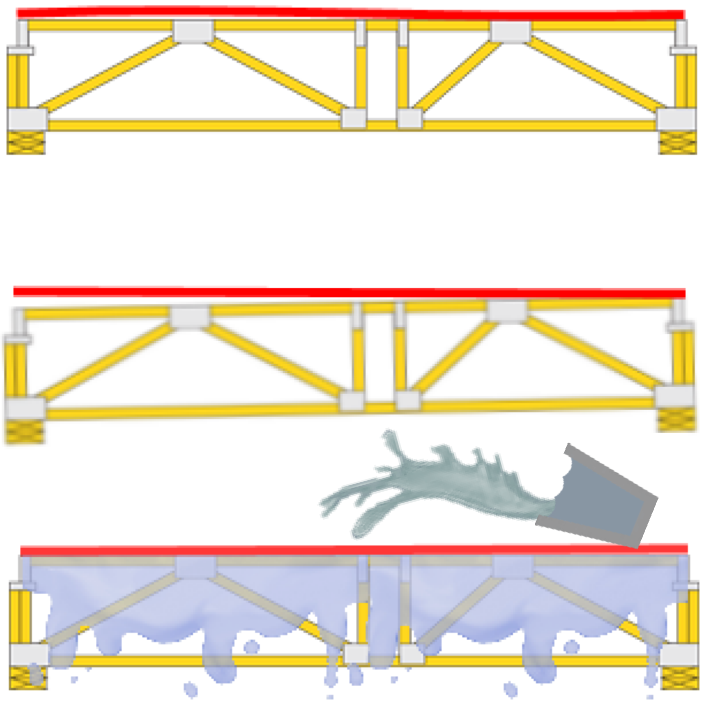
- In general, the provisional deflection criteria set by the IRC/IBC and its referenced standards are a short-term criteria.
- ANSI/TPI 1-2014 Section 7.6 provides guidance on how to predict time dependent deformation under long term loading:

- ANSI/TPI 1 Section 7.6 DEFLECTION
- 7.6.1 Method of Calculation.

$$\Delta LongTerm = Kcr \times \Delta LT + \Delta ST$$

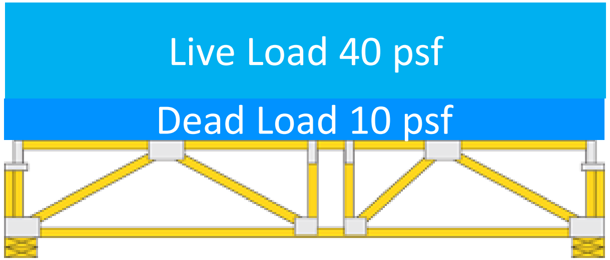
Analysis – Stone/Ceramic Tile

- Excessive deflection is not the only reason cracking occurs in brittle type tiles.
- Cracking in tiles can also be caused by
  - Uneven subfloor surface
  - Bearing height differential
  - Improper installation techniques for the subfloor or tile



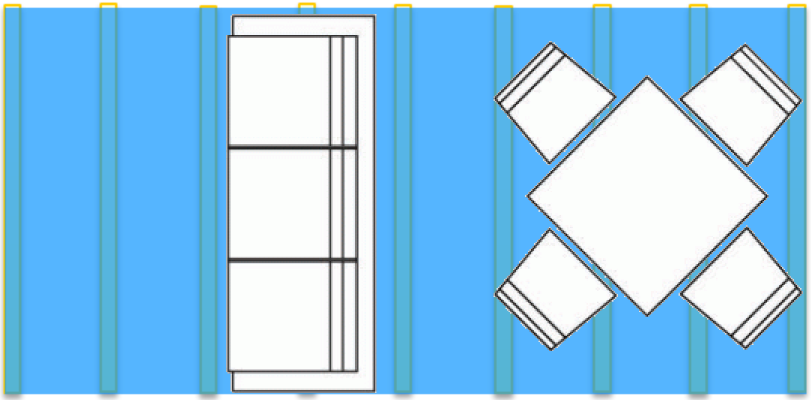
Analysis – Heavy Concentrated Loads

- Wood floor truss systems are commonly designed to carry a uniformly distributed load.
- The floor truss system is designed assuming this uniform load is applied over the entire floor area.



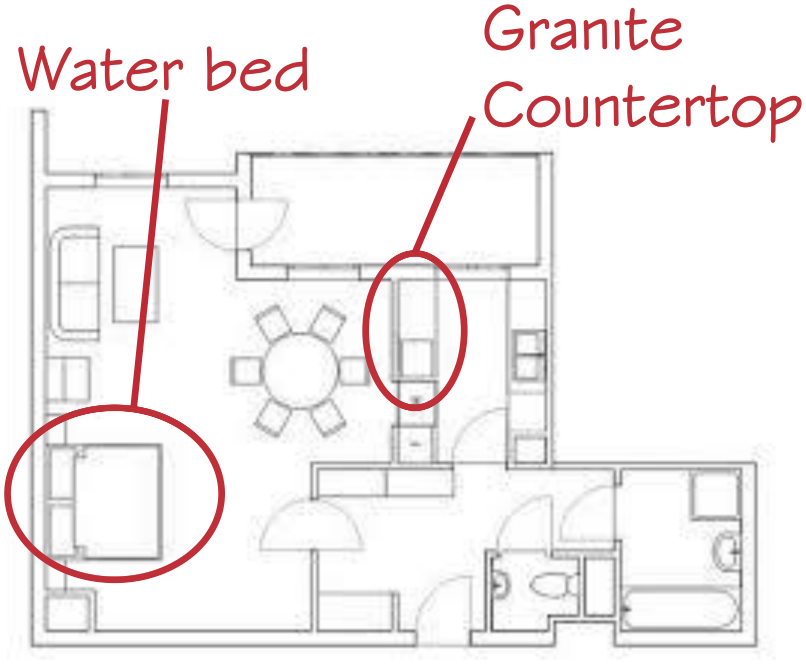
Analysis – Heavy Concentrated Loads

- Since, in reality, an entire floor area is never simultaneously loaded, this approach is usually conservative.
- This is unavoidable given the uncertainty of the live loads the floor will actually be subjected to.



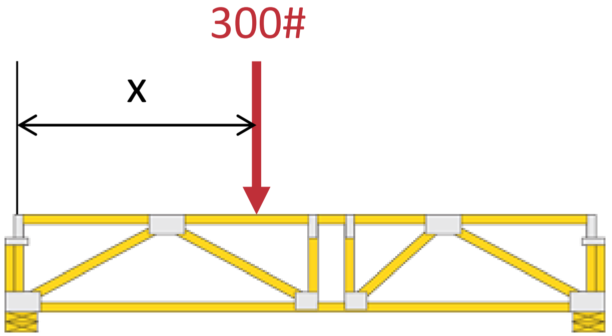
Analysis – Heavy Concentrated Loads

- Uniform loading may not be adequate to account for heavy concentrated loads.
- The building design drawings should always be checked to make sure any such loads are identified and accounted for in the floor design.



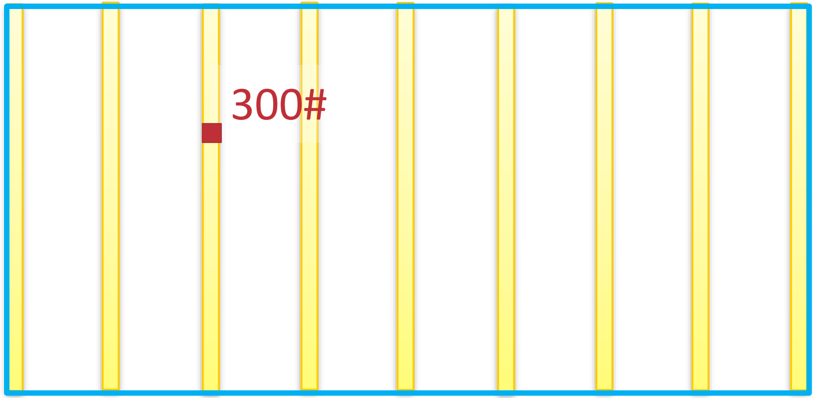
Analysis – Heavy Concentrated Loads

- 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.
- Although not required for residential buildings, it can be beneficial to consider a moveable concentrated load at critical locations on a structure's floor plan.



Analysis – Heavy Concentrated Loads

- 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 dwellings.
- The 300 lb. load need not be considered to act concurrently with the uniform live load.

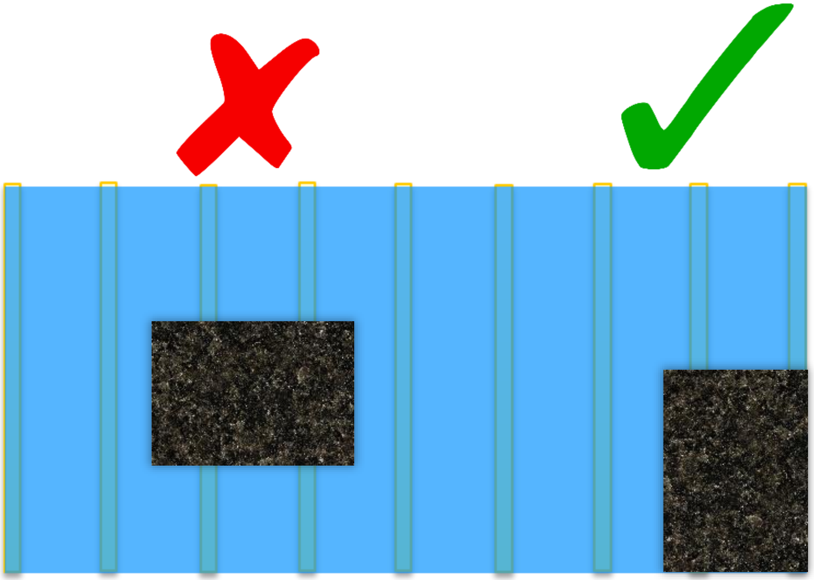


Analysis – Heavy Concentrated Loads

- 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).
- If a concentrated live load is not considered in the initial design, the following suggestions can be helpful:

Analysis – Heavy Concentrated Loads

- 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.



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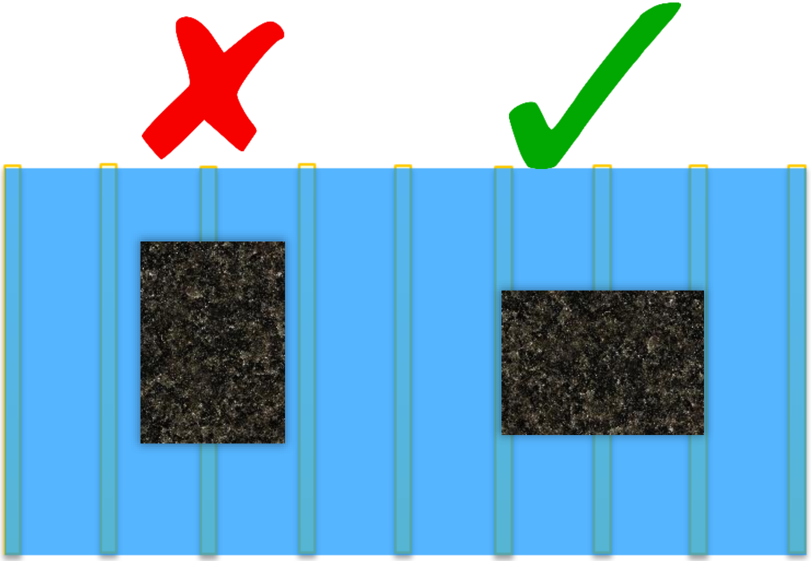
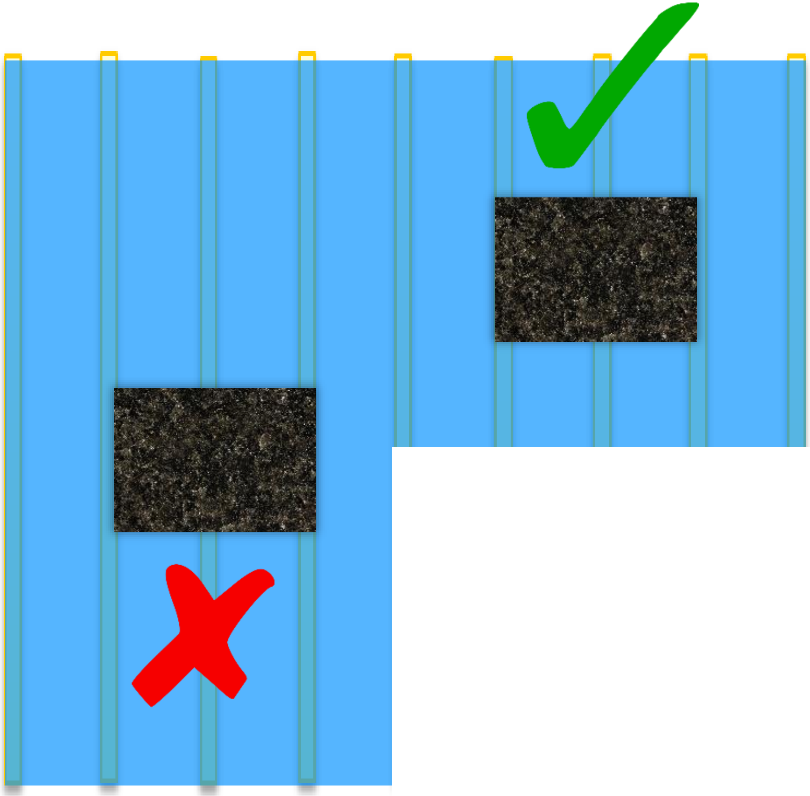
Analysis – Heavy Concentrated Loads

- Position concentrated loads such that they are carried by multiple floor trusses.



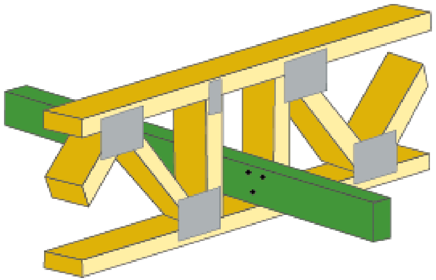
Analysis – Heavy Concentrated Loads

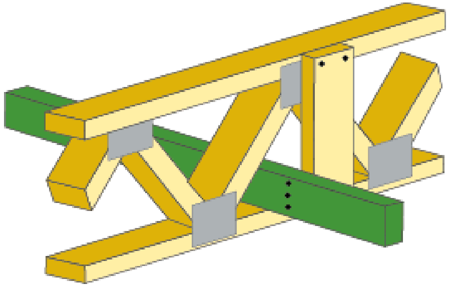
- Add concentrated loads to smaller rooms that have shorter, stiffer trusses (assuming trusses are the same size and spacing throughout the structure).



Analysis – Heavy Concentrated Loads

- Use proper strongbacks and bridging between trusses to increase interconnectivity and help distribute load more effectively.
  - Use minimum 2x6 nominal lumber oriented with the depth vertical.
  - Attach strongbacking to each truss with a minimum of three (3) 10d (0.131x3.0") nails. Shim the joint between the strongback and truss to ensure solid connection.
  - Spacing should not exceed 10'.





Analysis – 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, floors are able to span greater distances, which makes them more flexible and susceptible to vibrations.

MAXIMUM ALLOWABLE SPANS (Δ_{LL} = $^{Span}/_{360}$, Δ_{TL} = $^{Span}/_{240}$) [1, 2]

Truss On-Center Spacing	4 x 2 Floor Truss Depth (d)						
	12"	14"	16"	18"	20"	22"	24"
16"	23' 11"	27' 5"	30' 5"	32' 4"	34' 1"	35' 10"	37' 6"
19.2"	22' 9"	25' 10"	28' 5"	31' 3"	32' 6"	33' 5"	35' 10"
24"	21' 5"	23' 8"	26' 5"	28' 4"	29' 3"	29' 10"	32' 6"

MAXIMUM ALLOWABLE SPANS (Δ_{LL} = $^{Span}/_{480}$, Δ_{TL} = $^{Span}/_{360}$) [1, 2]

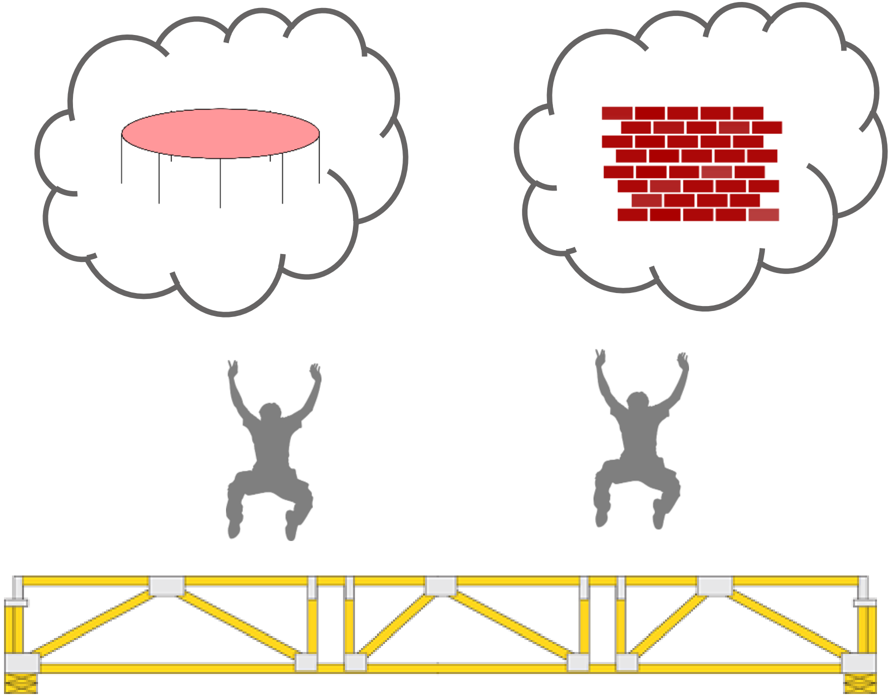
Truss On-Center Spacing	4 x 2 Floor Truss Depth (d)						
	12"	14"	16"	18"	20"	22"	24"
16"	21' 5"	24' 0"	26' 7"	29' 0"	31' 2"	32' 7"	34' 10"
19.2"	20' 1"	22' 7"	24' 10"	27' 2"	29' 4"	31' 6"	33' 5"
24"	18' 7"	20' 11"	23' 0"	25' 1"	27' 1"	28' 10"	30' 0"

MAXIMUM ALLOWABLE SPANS (Δ_{LL} = $^{Span}/_{720}$, Δ_{TL} = $^{Span}/_{360}$) [1, 2]

Truss On-Center Spacing	4 x 2 Floor Truss Depth (d)						
	12"	14"	16"	18"	20"	22"	24"
16"	16' 9"	19' 0"	20' 11"	22' 8"	24' 6"	26' 3"	27' 7"
19.2"	15' 10"	17' 7"	19' 7"	21' 4"	22' 11"	24' 6"	26' 1"
24"	14' 8"	16' 5"	18' 0"	19' 8"	21' 3"	22' 7"	24' 1"

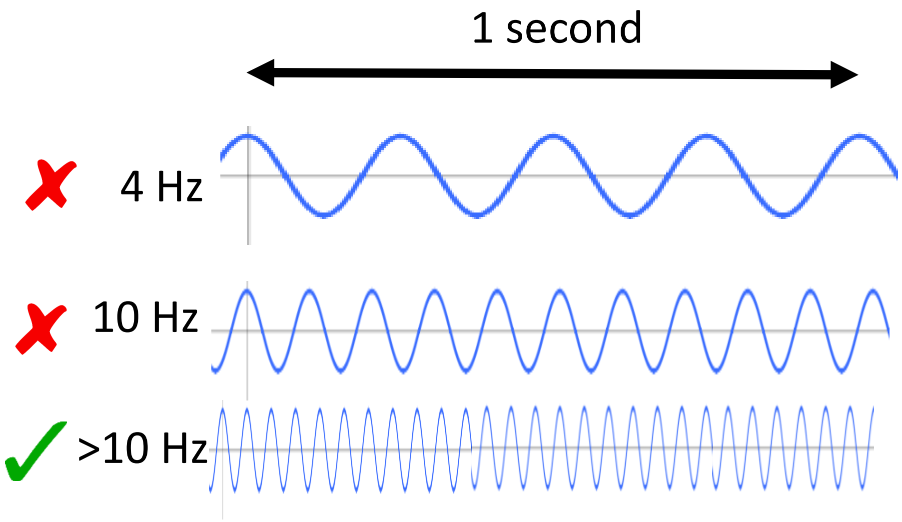
Analysis – Floor Vibration

- Vibrations in a floor system can be caused by something as simple as pedestrian foot traffic.
- Vibration can be very subjective.
- What one person considers to be an annoying level of vibration might be completely unnoticeable to someone else.



Analysis – Floor Vibration

- The natural frequency of a structural member 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.
- Humans are most sensitive to vibrations with frequencies between 4 and 10 Hz.

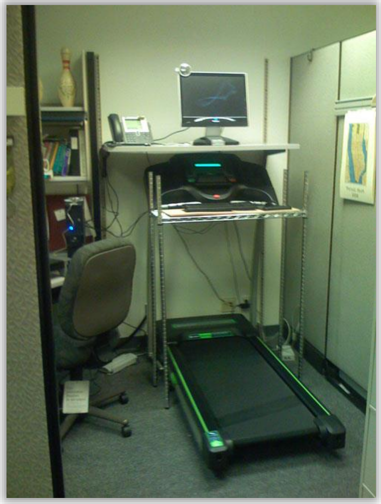


Analysis – Floor Vibration

- Just because a floor system meets building code requirements for serviceability, does not mean it is immune to vibration issues.
- Vibration issues are especially prevalent in "sleeping rooms", which can be designed using a uniform live load of only 30 psf rather than the typical 40 psf in a residential structure.

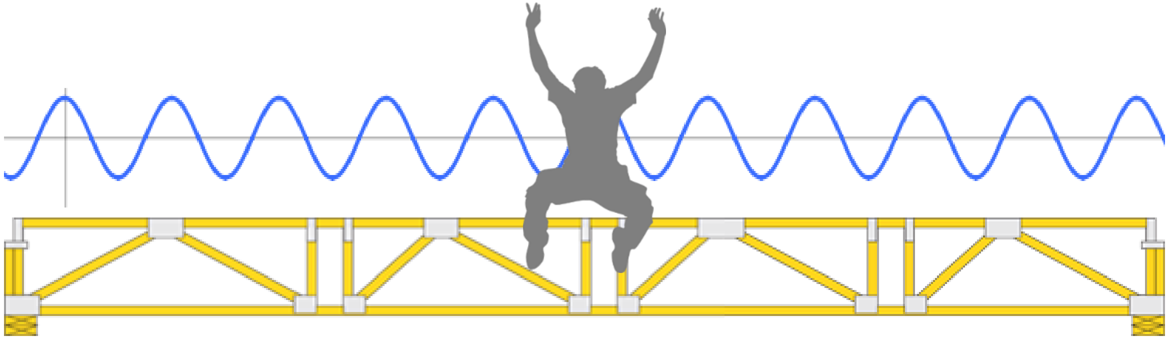
Analysis – Floor Vibration

- Rooms originally designed as sleeping rooms are often repurposed, and end up seeing much more human activity than the design intended.



Analysis – Floor Vibration

- At 30 psf and L/360 the floor trusses can be designed more shallow and flexible, while still meeting code.
- A floor system with flexible trusses will have a low natural frequency and will invite unwanted vibrations.



Analysis – Floor Vibration

- Most designers use a floor span-to-depth limitation (L/d = span in inches divided by 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.

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"

Analysis – Floor Vibration

- There are three main methods to reduce vibration.
- The easiest method is to **increase the deflection criteria** used in the floor design above the code minimum.
  - This will increase the stiffness of the floor system, especially when dealing with longer truss spans.

Δ_{LL} = L/360, Δ_{TL} = L/240

↓

Δ_{LL} = L/480, Δ_{TL} = L/360

↓

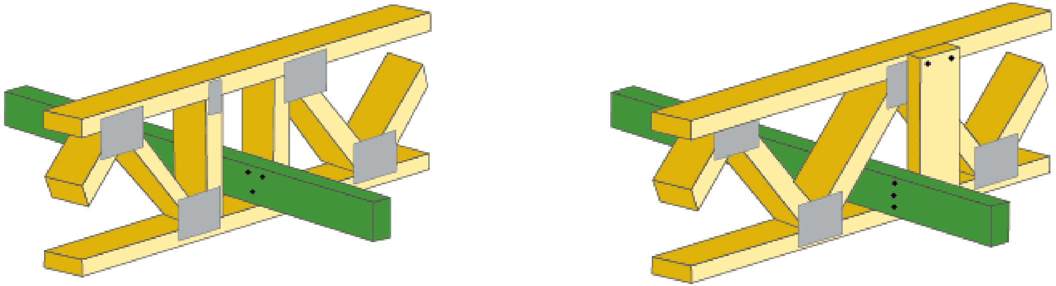
Δ_{LL} = L/720, Δ_{TL} = L/480

Analysis – Floor Vibration

- Another method is to **improve the floor sheathing connection to the floor system**.
  - Glue in combination with screws will yield the greatest results.
  - This will improve the performance of the floor diaphragm and help distribute localized forces to neighboring floor trusses.

Analysis – Floor Vibration

- A third method involves **attaching strongback bracing** as recommended on floor trusses.

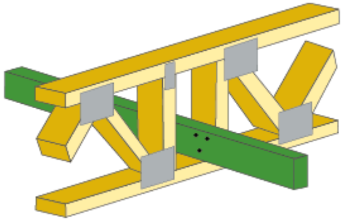
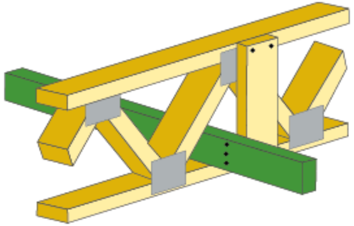


Conclusion

- By designing a floor system to be slightly above and beyond the minimums required by the building code, several issues can be addressed.
- What follows are industry recommendations to address special floor loading to increase floor system stiffness and limit deflections.

Conclusion

- Glue the underlayment to the subfloor and fasten with screws rather than nails, and install strongbacks.

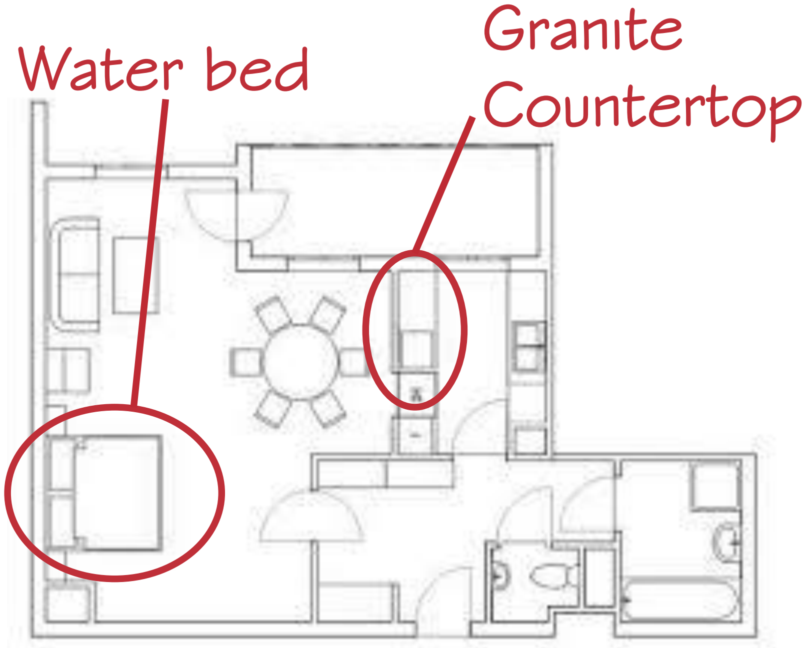

Conclusion

- The Building Designer should establish what deflection, load and on-center spacing requirements apply to any particular floor covering at the time of design.

MAXIMUM ALLOWABLE SPANS (Δ_{LL} = Span/360, Δ_{TL} = Span/240) [1, 2]							
Truss On-Center Spacing	4 x 2 Floor Truss Depth (d)						
	12"	14"	16"	18"	20"	22"	24"
16"	23' 11"	27' 5"	30' 5"	32' 4"	34' 1"	35' 10"	37' 6"
19.2"	22' 9"	25' 10"	28' 5"	31' 3"	32' 6"	33' 5"	35' 10"
24"	21' 5"	23' 8"	26' 5"	28' 4"	29' 3"	29' 10"	32' 6"

Conclusion

- All parties in the design process should be aware that as truss spans and material weight increase, so does the risk for serviceability and performance issues.
  - Truss Designers should get information from the Building Designer in writing so the trusses are designed stiff enough to avoid serviceability issues.

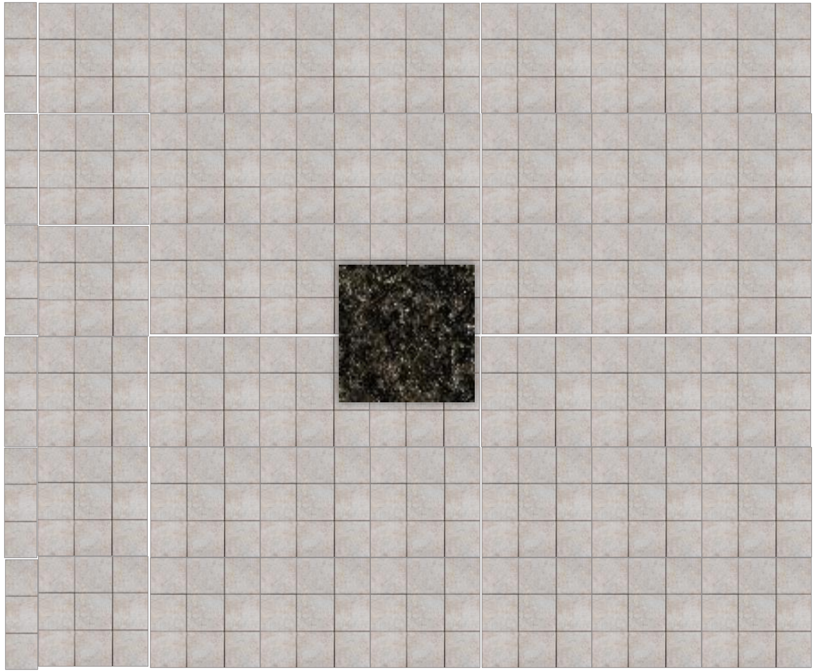


Conclusion

- Ceramic Tile:
  - Suggested live load and total load deflection of L/360
  - Add weight to top chord dead load as directed by manufacturer (use 7 psf if weight is unknown)
- Stone Tile:
  - Suggested total load deflection of L/720
  - Add weight to top chord dead load as directed by manufacturer
- Granite Countertops:
  - Unless exact locations are specified, add an additional 20 psf to the top chord dead load for counters with up to 2 inches of granite

Example – Code Compliant vs Special Loading

- 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.



Example – Code Compliant vs Special Loading

- Assumptions:
  - 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

Example – Code Compliant vs Special Loading

- 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):

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

Example – Code Compliant vs Special Loading

- The standard deflection limit of L/360, or 0.733" (264/360) in this example, is satisfied.
- However, the recommended limit for floors supporting stone tiles of L/720, or 0.367" (264/720) in this example, 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.

Example – Code Compliant vs Special Loading

- 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)

Example – Code Compliant vs Special Loading

- One possible solution could include:
  - Increase the truss depth to 21"
  - Use SP No. 1, 2x4 chords, which have a greater modulus of elasticity
  - Reduce the joist spacing to 19.2" o.c.
- Doing so yields the following deflection:
- $\frac{5(96^{lbf}/_{ft})(\frac{1ft}{12in})(264in)^4}{384\left(1{,}700{,}000^{lbf}/_{in^2}\right)(1000.1in^4)} + \frac{200lbf\frac{19.2}{24}(264in)^3}{48\left(1{,}700{,}000^{lbf}/_{in^2}\right)(1000.1in^4)} = 0.334in$

SBCA

Example – Code Compliant vs Special Loading

- 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.

Example – Code Compliant vs Special Loading

- To determine if vibration will be an issue, it can be calculated that a beam of any length having a dead load deflection below 0.055" will have a natural frequency that is greater than 15 Hz, which places it outside of the range of human sensitivity.
- This rule of thumb, from a paper by Castle and Pormerleau, is derived by combining the equations for calculating the natural frequency and deflection of a beam to output a deflection value below which vibration should not be an issue.

Example – Code Compliant vs Special Loading

- 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.
- Note that this criteria is more restrictive for longer spans than other criteria.

References

- 2012 IRC Section R301.7
- 2012 IBC Section 1604.3
- Marble Institute of America, Installation/General Information, 2011
- Tile Council of North America
- SBCA Structural Details
- Serviceability of Floor Systems in Existing Residential Timber Frame Structures, Thomas Castle and David Pomerleau