When Fashion Affects Structure—Floor Design Considerations for Preventing Tile and Stone Cracks

By Frank Woeste and Peter Nielsen

Two kinds of designers are involved in home construction—design professionals responsible for the structure and the interior-focused designers responsible for the final appearance. Although these roles can overlap, it is important for design professionals to be aware of in-service demands that will result from interior fashion choices.

In our April 2018 continuing education course at Virginia Tech, we presented and discussed a unit on "Specifying and Constructing Floors to Accommodate Ceramic Tile and Stone." The 1-hour unit focused on three aspects of floor design that are likely to impact the performance of ceramic tile and stone installations in-service:

1. The use of an adequate design dead load that includes the weight of the hard-surface installation method,
2. The relative importance of joist stiffness and sheathing stiffness in preventing cracks, and
3. Accounting for substantial concentrated loads, such as the weight of kitchen islands with stone or polished concrete surfaces.

This article will review these three aspects and offer guidance for designers and others interested in the structural performance of their products after construction.

Adequate Design Loads for Floors Supporting Tile and Stone

An inadequate specification of the dead load (weight) of tile or stone "Installation Methods" by the Design Professionals (DPs) can:

a) Cause wood-frame floors to be over-stressed in-service, and/or

b) Yield excessive "creep deflection" that can cause cracked grout and tiles in-service.

An adequate dead (sustained) load specification is important for a reliable hard surface installation.

One way to think of "creep deflection" is to imagine an overloaded shelf in a bookcase. Over time, the weight of the books can cause the shelf to bow. The deformation is not visible immediately, but the damage can be permanent. In the case of a floor, not only is the effect on the floor itself an issue, but also the effect on the flooring. The "creep" occurs beneath the flooring, so the flooring is no longer on top of a level surface, and the result can be cracking of tiles and grout.

Weight of Hard-Surface Installation Methods

Dead load data for the weights of tile and stone installations have been tabulated in Appendix B of the **2017 Tile Council of North America (TCNA) Handbook for Ceramic, Glass, and Stone Tile Installation** (www.tcnatile.com/products-and-services/publications.html). Appendix B is an invaluable design resource as it contains the typical weight of dozens of "Installation Methods" for ceramic and glass tile (hereafter, tile) and stone installed on wood-floor framing.

The following is a sample of *2017 TCNA Handbook* Wood-Framing Installation Methods. The Installation Method Dead Load is the weight of the materials above the subfloor. Total Dead Load in the rightmost column is based on an assumed dead load of 10 psf for the subfloor, joist, and ceiling.

Table 1. Sample of Installation Methods from the *2017 TCNA Handbook.*

Page	**TCNA** Method Number	Description	Installation Method Dead Load above "Subfloor" (psf)	Total Dead Load (Framing, drywall & subfloor, **10 psf** assumed)
138	RH122-17	**16"oc, 23/32"** T&G Ply. Subfloor ¾" Gyp Underlayment Hydronic Tubing	19	29
150	F141-17	16"oc,19/32' T&G Ply. Subfloor 1-1/4" Mortar Bed	21	31
158	F150-17	16"oc, 19/32" T&G Subfloor, 15/32" Ply. Underlayment	7	17
162	F144-17	16"oc, 19/32 or 23/32" T&G Ply. **Cement Backer Board**, ¼, 7/16, or ½"	8, 9, or 10	18-20
174	F149-17	24" oc, 23/32"T&G Ply. Subfloor, 19/32" Underlayment	7	17
358	F250-17 (Natural Stone)	16"oc, 19/32" T&G Ply. Subfloor, 15/32"Ply. Underlayment, and (various) Backer Board Products	11-14	21-24
182	F180-17 Ceramic Tile, Glass Tile	**16"oc, 23/32" T&G Ply**. Subfloor, Poured Gypsum Underlayment (Min. ¾"), Bonded Membrane	12 (Add 2¼ psf per additional ¼" poured gypsum)	22

Upon review of Table 1, a *design* dead load of 10 psf is not adequate when the floor covering is tile or stone. This structural issue requires the attention of all professionals involved in the specification of the hard surface/installation method, floor system design, and framing inspectors.

A snapshot from the IRC (Figure 1) indicates that an inadequate assumed dead load can be a "code issue" with respect to maximum span, and, in addition, the extra loading can contribute to additional creep deflection that can result in tile, stone, and grout cracks.

TABLE R502.3.1(2)
FLOOR JOIST SPANS FOR COMMON LUMBER SPECIES
(Residential living areas, live load = 40 psf, L/Δ = 360)[b]

JOIST SPACING (inches)	SPECIES AND GRADE		DEAD LOAD = 10 psf				DEAD LOAD = 20 psf			
			2 × 6	2 × 8	2 × 10	2 × 12	2 × 6	2 × 8	2 × 10	2 × 12
			Maximum floor joist spans							
			(ft. - in.)	(ft. - in.)	(ft. - in.)	(ft. - in.)	(ft. - in.)	(ft. - in.)	(ft. - in.)	(ft. - in.)
	Douglas fir-larch	SS	11-4	15-0	19-1	23-3	11-4	15-0	19-1	23-3
	Douglas fir-larch	#1	10-11	14-5	18-5	22-0	10-11	14-2	17-4	20-1
	Douglas fir-larch	#2	10-9	14-2	18-0	20-11	10-8	13-6	16-5	19-1
	Douglas fir-larch	#3	8-11	11-3	13-9	16-0	8-1	10-3	12-7	14-7

Figure 1. Table R502.3.1(2) Floor Joist Spans for Common Lumber Species.

The content of the IRC table suggests why the 2015 IRC span table for joists has two sections—one for an assumed dead load of 10 psf (carpet, vinyl, wood) and the other for a dead load of 20 psf (typical residential hard surfaces).

Tile Cracks and Related Engineering Science

Tile cracks typically form *on top of* and *parallel to* the joist. The overriding practical question is:

- With respect to floor design, what is more important for protecting tile or stone from potential cracking, joist deflection/stiffness (L/xxx) or floor sheathing thickness/stiffness?

Keith Bretzfield, a former graduate student at Virginia Tech, applied engineering science of beams to shed light on the question and published the results in 2003[1].

From engineering science for a beam,

$$1/\rho = M/EI$$

where ρ is the "radius of curvature" of the beam at the location of bending moment (M), and
EI is joist stiffness.

To translate the expression, the amount of "bend" at any cross section of a floor joist (or sheathing) span is proportional to the bending moment divided by the product of the Modulus of Elasticity (E) and moment of inertia (I) of the section. Referring to Figure 2 and the tile depicted, joists and subfloor/substrates with the largest possible "ρ" will minimize the stresses induced in the tile from bending action of the joists and sheathing/substrates, respectively.

[1] Bretzfield, K. T. and F. E. Woeste. 2003. Joist curvature verses sheathing curvature and the probable role of each on ceramic tile performance. TTMAC HARDSURFACE Magazine, TTMAC, 30 Capstan Gate, Unit 5, Concord, Ontario, Canada.

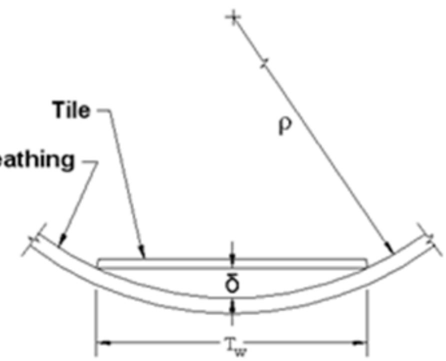

Figure 2. Depiction of stresses induced from bending action of joists and sheathing/substrates.

Bend of Joists verses Sheathing

Using a total floor load of 60 psf, we calculated the radius of curvature, ρ, for several IRC joist spans at maximum bending moment and the results are given in Table 2.

Table 2. Radius of curvature (ρ) for 2015 IRC maximum spans for 2x10 No. 2 Southern Pine joists and 40-20 psf loading (and L/360 live-load deflection limit).

Live Load (psf)	Dead Load (psf)	Joist Spacing (ins.)	Span (max) (ft-ins)	M (in-lb)	ρ= EI/M (ins.)[1]
40	20	16	12-10	19,761.	6,983.
40	20	19.2	11-8	19,600.	7,041.
40	20	24	10-5	19,531.	7,066.

[1]EI for 2x10 No.2 Southern Pine equals 98.93 in4 x1,400,000 lb/in2, or 1.38x108 in2-lb. See 2015 NDS Supplement, pp.14 and 40, for 2x10 design data.

The average radius of curvature for the joists is about 7,000 inches.

Spreading the News

Two more articles from this *All Things Wood* column by Frank Woeste have just been reprinted!

From February 2018: "Safety Information for Post-Frame Truss Installation," reprinted in the May 2018 issue of *Rural Builder*

From August 2017: "Evaluating an Existing Residential Deck," reprinted in the May 2018 issue of *The ASHI Reporter – Inspection News and Views from the American Society of Home Inspectors*

Nice work, Frank!

Background: How Tile Installation Methods are Tested

A cross-section of the ASTM 627 Robinson-Type Floor Tester is shown in Figure 3.

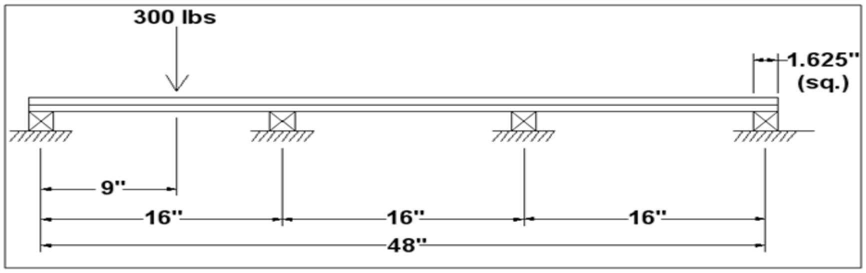

Figure 3. Cross-sectional view of the test specimen assembly of the Robinson-Type Floor Tester (ASTM C627).

The ASTM C627 standard for testing tile *Installation Methods* includes a rotating platform that applies up to 300 lb at three locations. The loads are applied through three 4"-diameter swivel caster wheels that are each separated by 120°. The test requires three different sets of three wheels, which are comprised of soft rubber, hard rubber, and steel. Different test cycles require different wheel compositions.

The test does not include the deflection of the joists and butt joints in the subfloor and underlayment that are present in an actual construction. Likewise, our calculations to follow represent a best case scenario for an actual tile installation because a constructed floor contains joists that deflect under loads and the floor sheathing is butted at the 4' x 8' panel ends.

We calculated ρ for four (wood sheathing) installation methods using the following assumptions:

1. A 300 lb concentrated load in the first sheathing span at the point of maximum moment, and
2. No composite action between the subfloor and underlayment.

Table 3: Radius of curvature (ρ) for first sheathing span at maximum bending moment when loaded by a 300 lb concentrated load as applied in the ASTM C627 test of Installation Methods. (Note: For 16 oc, M=927 in-lb; for 24 oc, M=1301 in-lb.)

2017 TCNA Method	Joist Spacing (in.)	Subfloor T&G (in.)	Under-lay-ment (in.)	Uncoupling Membrane	ρ = (EI/M)
F144 Residential	16	19/32	CBB (¼")	--	221
F144 Light Comm.	16	23/32	CBB (1/4")	--	345
F147	24	23/32	3/8	Yes	284
F149	24	23/32	19/32	Optional	404

For the first wood sheathing span under 300 lb concentrated load, calculated ρ for four TCNA Methods was about 300 inches.

Summary—Relative Importance of Joist Stiffness (L/xxx) versus Sheathing Stiffness

1. Floor sheathing bend as determined by (1/ρ) under a concentrated load is about **23X** greater than the bend of the joist under 60 psf uniform live and dead load.

2. Based on field evidence and the engineering analyses presented (above), the structural designer for floor areas supporting tile or stone should place the *greater* emphasis on subfloor/sheathing specification *relative to* joist framing specifications.

3. The analyses and recommendation as summarized above did not include the impact of end butt-joints in the subfloor and the impact of *differential* joist deflection due to concentrated loads, girders, and points of bearing that can cause differential deflections of framing.

Practical Specifications for Concentrated Floor Loads

For ceramic tile, the 2017 *TCNA Handbook* has "deflection requirements" listed for all framed floor system Installation Methods that cites the IRC and IBC as well the following requirement:

> "For ceramic tile installations, maximum allowable floor member live load and *concentrated load* deflection for framed floor systems shall not exceed L/360, where "L" is the clear span length of the supporting member per applicable building code."

In view of this language, uniform live load and concentrated load deflections in residential/multi-family applications are a requirement for the "supporting member" or floor framing system. The TCNA "concentrated load deflection" requirement is in *addition to* the requirements of the applicable IRC, as we are not aware of a concentrated dead-load deflection requirement in the 2015 IRC (or earlier editions). Knowing that concentrated loads such as kitchen islands may be shown on the Construction Documents, it is incumbent upon the design team to specify concentrated loads for the Component Manufacturer's (CM) use, or other measures to address the expected deflection from concentrated loads.

An example of a modern and large kitchen island in residential construction is shown in Figure 4. The framing design question is—given the footprint of the island, what is a reasonable dead load specification?

The density of natural stone can vary between 160 and 200 lbs/ft². As such, a stone thickness of 1¼" (30 mm) can weigh between 16.7 and 20.8 psf. Considering the weight of the cabinet, doors, and shelves, the island weight without contents approaches 30 psf (a sustained load).

The fact that it is a "sustained load" is very important, as "creep" is caused by sustained loads. Assuming the total dead load of the island with contents is 40 psf, it should not be considered equivalent to a 40 psf live-load due to "creep" deflection from sustained loads. Simply stated, an L/360 design based on a 40 psf live-load can experience additional creep deflection in-service due to a 40 psf "sustained load" with the actual joist deflection approaching L/180 (using a creep factor of 2.0 from ANSI/TPI 1-2014).

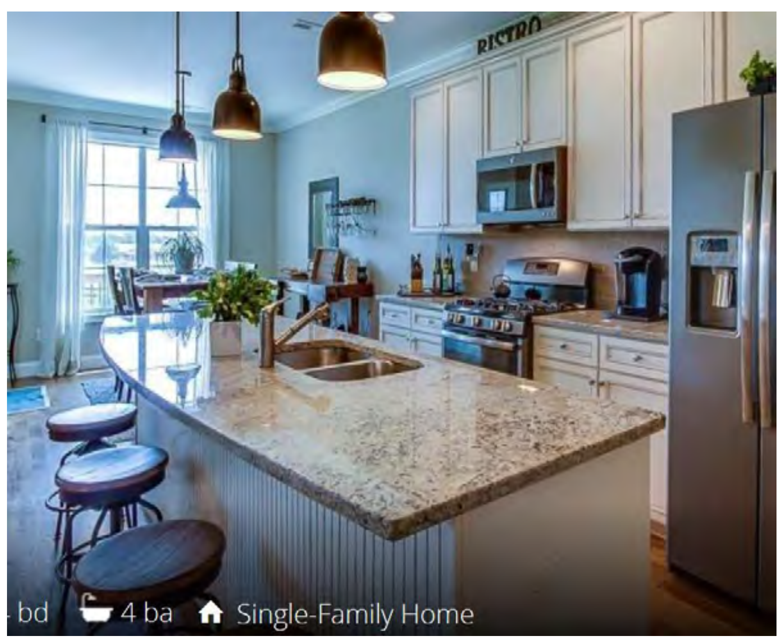

Figure 4. Kitchen island oriented parallel to the floor framing. For this case, almost the entire weight of the island would be supported by two framing members at 24" on-center.

Prescriptive Specification for Residential/Multi-Family Concentrated Loads

After spending a lot of time on this subject prior to our 2018 short course, we contacted Scott Coffman, P. E. (Constructionscience.org) for feedback from a professional with 35 years of wood-frame design experience. When asked for his thoughts on a "prescriptive design specification" when modern kitchen islands are involved in a project, his comments were in-depth but started off with three easily-understood conditions for an effective prescriptive specification:

1. Can it easily be understood,
2. Can it feasibly be implemented, and
3. Can it be inspected.

Based on the 30+ years of experience we've had interacting with DPs in educational programs, we've found that most DPs are not aware of the impact of "sustained loads" verses "live loads" in terms of laboratory-tested creep-behavior of solid-sawn, I-Joists, and floor trusses subject to large sustained loads. For an "engineered design approach" to the issue, very specific load data and the footprint of the island would need to be specified along with accurate "creep factors" for the sustained load level involved. Thus, in the first author's opinion, the "engineered design approach" violates Conditions 1 and 2 above: the design issues are very complicated and a reliable implementation is unlikely.

In view of the practical constraints cited, we offer two ***prescriptive options*** for Contractors, Homebuilders, and DPs to communicate the existence of substantial concentrated loads produced by modern kitchen islands, and, as such, provide a measure of protection for ceramic tile/stone floor installations in residential/multi-family application.

For Solid-Sawn and I-Joists

- Joist spacing beneath kitchen islands shall be reduced by one-half and indicated on the joist framing plan.

For Floor Trusses

- Floor trusses beneath kitchen islands shall be doubled.

We believe these prescriptive specifications are a practical "default option" to actual load specifications for kitchen islands by Contractors, Homebuilders, and DPs for residential/multi-family projects. Of course, with specialized engineering knowledge of the long-term deflection behavior of wood-joist products, in-service island sustained loads, and the island footprint, a more economic design for hundreds of identical units might be possible and cost effective.

Conclusions

The design of residential and multi-family floors has become more complicated due to the widespread use of hard surfaces and the placement of heavy items, such as large kitchen islands, in the center section of the framing spans. When the uniform and concentrated loads, including creep deflection, are not properly accounted for in the floor system design, in-service performance issues of the hard surfaces can be expected.

Based on our analyses and experience, we offer the following suggestions for consideration by the design team.

1. Prepare Construction Documents that contain:
    a) the TCNA tile/stone Installation Method,
    b) the weight of the installation method,
    c) the footprint of kitchen island (and other heavy equipment), and
    d) a specification that joists shall be doubled (or spacing reduced by 1/2) beneath the island.
2. Require floor system designs based on a "total load" that includes the actual weight of the TCNA Installation Method for the hard surface listed in the Construction Documents.
3. Upgrade the subfloor thickness above the thickness specified for the TCNA Installation Method in the Construction Documents to improve the predicted bending behavior of the floor sheathing under a 300 lb concentrated load. (For example, a 23/32" T&G plywood panel has a bending stiffness (EI) of 320,000 (lbf-in.^{2}/ft) when installed as a subfloor, whereas a 7/8" panel has an EI of 500,000 (lbf-in.2/ft). The EI of a 7/8" subfloor panel is 1.56 times greater than the EI of the 23/32" panel, thus providing substantially more protection for the hard surfaces.)
4. Require strongback bracing for floor trusses in an effort to protect tile and stone floors against potential hard surface damage due to differential deflection of the joists (and to improve the likely vibrational performance of floors as well).
5. Offer Customers (homebuyers and owners) floor framing and subfloor "upgrades" for added protection against the likelihood of tile and grout cracks and annoying floor vibrations.

Historically, the design rules in our residential construction building codes addressed a concern for plaster cracking (L/360 live-load only deflection) and a floor collapse (40 live load plus 10 psf dead load) when solid-sawn joists and wood flooring were the norm. Fast-forward 100 years, longer joist spans, hard surfaces (ceramic, glass, and stone), and large kitchen islands are common, yet the current IRC does not include provisions to address the intrinsically inelastic nature of hard surface flooring. To do so, the design team must take into account *concentrated* floor loads and *total* load deflection to mitigate the serviceability issues that stem from the use of hard surface flooring. Hopefully, this article will provide motivation for a coordinated effort by the design team to address serviceability issues for modern construction with hard surface flooring.

Letters to the Editor

By a Letter to the Editor, we invite comments and ideas on the design of floor framing to reliably accommodate tile, stone, and kitchen island type loads in-service. Please send comments to Anna Stamm.

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