Joist Curvature versus Sheathing Curvature and the Probable Role of Each on Ceramic Tile Performance

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Introduction

The cracking of ceramic tile and grout is a common problem in residential floor applications. Prior to 2001, the design criteria set forth by the Tile Council of America (TCA) in the *Handbook for Ceramic Tile Installation* stated "design floor areas over which tile is to be applied to have a deflection not greater than L/360 of the span" (TCA, 2000). A common misconception among joist designers was that this L/360 deflection requirement in TCA was the same L/360 building code deflection limit for residential floor joists under a *uniform* design live load of 40 psf. In 2001, the language of the provision was changed to "design floor areas over which tile is to be applied to have a deflection not greater than L/360 of the span when measured under 300 lbs. concentrated load (see ASTM C627)" (TCA, 2001). Thus, in 2001, it became clear to us that there were two L/360's involved and no known relationship between the two L/360's could be established by engineering analyses.

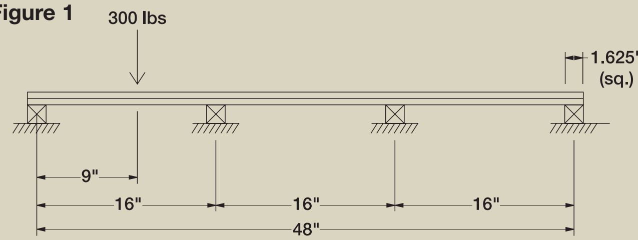
One widely accepted cause for tile cracking is the deflection of the floor system beneath the tile. The primary objective of this paper is to demonstrate that curvature, rather than deflection, may be the primary geometric factor that causes cracking of the tile and grout. A secondary objective is to differentiate between the curvature of the sheathing and the curvature of the joists in a floor assembly.

ASTM C627

The ASTM C627 test is the standard test method for evaluating ceramic tile installation systems. The C627 testing procedure utilizes the Robinson-Type Floor Tester to evaluate "complete ceramic floor tile installation systems for failure under loads" (ASTM, 1993). Per the 2001 TCA specifications, all plywood floor assemblies must be rated using this test. The Robinson-Type Floor Tester consists of a 4-ft.-square plywood assembly. The plywood is placed on four 1-5/8" square wooden members, simulating joist supports, four feet in length. These "floor joists" are fully supported along their length by a concrete base, eliminating any joist deflection from the test. The plywood is installed with the face grain perpendicular to the floor joists to ensure maximum stiffness.

The load is applied to the assembly utilizing three caster wheels with differing applied loads dependent on the load cycle. These dynamic, concentrated loads pass over the tile system in a continuous circular motion, causing the plywood to deflect throughout the testing procedure. Figure 1 depicts one concentrated load of the Robinson-Type Floor Tester and the cross-section of the subfloor and underlayment that rests on 2x2's (fully supported by a 4' x 4' concrete slab not shown).

Figure 1



Cross-sectional view of the test specimen assembly for the Robinson-Type Floor Tester with applied load creating maximum moment on the floor sheathing layers.

Figure 1 depicts the 16" joist spacing case with the 15" load radius as specified by ASTM C627. The maximum moment will be created 9" from the outside support. This maximum moment was the basis of determining the curvature of the plywood assembly.

Curvature of Floor Sheathing

The curvature of a beam, C, is defined as the reciprocal of the radius of curvature, ρ. The radius of curvature is the radius of the elastic curve of the deflected beam. The curvature of a beam can be calculated using Equation 1.

$$C = \frac{1}{\rho} = \frac{M}{EI} \qquad [1]$$

where:

- ρ = radius of curvature,
- M = bending moment,
- E = modulus of elasticity, and
- I = moment of inertia.

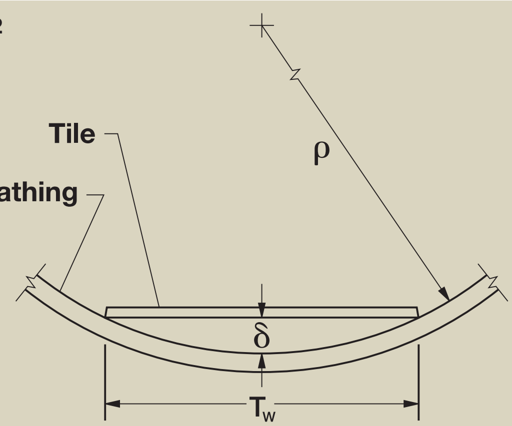
As the formula dictates, curvature is directly proportional to the applied moment at the section of the beam in question. Therefore, the point on the beam with the highest moment will have the highest curvature, C, or minimum radius of curvature, ρ. This point on the beam shown in Figure 1 will have the greatest deformation caused by the bending moment, and it is believed to be the critical point on the beam (sheathing span) that may contribute to tile cracking and grout failure.

Figure 2 represents a model of a tile and sheathing interface showing an exaggerated gap that would occur beneath one tile assuming no adhesive contact between the tile and sheathing. The width of the tile is represented as T_W. The relationship between the gap distance, δ, the radius of curvature, and the tile width can be seen in Equation 2.

$$\delta = \rho - \frac{1}{2}\sqrt{4\rho^2 - T_W^2} \qquad [2]$$

Assuming a constant moment over the width of the tile, as the width of the tile is increased, the gap distance, δ, will increase. As the radius of curvature is increased, the net effect will be to decrease the gap distance.

Figure 2



The tile and sheathing interface model showing an exaggerated gap between the single tile and the floor sheathing.

TCA Residential Plywood Assemblies

The 2002 Edition of the *Handbook for Ceramic Tile Installation* offers four recommended plywood subfloor assemblies that can be used for residential ceramic tile installation. Table 1 shows the minimum radius of curvature for the 16" and 24" joist spacing assemblies.

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Table 1. *Minimum radius of curvature for TCA-2002 subfloor layer and overlay layer specifications.*

TCA Assembly	Subfloor Layer	Overlay Layer	EISubfloor ($lb\text{-}in^2$)	EIOverlay ($lb\text{-}in^2$)	Mmax (lb-in)	ρmin (in)
F142-02	19/32" 20 oc Rated Sturdi-I-Floor or Rated Sheathing	19/32" 20 oc Rated Sturdi-I-Floor or Rated Sheathing	221,400	221,400	927	526
F147-02	23/32" 24 oc Rated Sturdi-I-Floor or Rated Sheathing	3/8" 24 oc Rated Sheathing	347,400	70,200	1301	353
F149-02	23/32" 24 oc Rated Sturdi-I-Floor or Rated Sheathing	23/32" 24 oc Rated Sturdi-I-Floor or Rated Sheathing	347,400	347,400	1301	588

When determining the curvature of the sheathing systems, no composite action between layers and no effects due to any uncoupling system were factored into the calculations. The radius of curvature ranges from a minimum of 353 inches for the F147-02 assembly to a maximum of 588 inches for the F149-02 assembly. The only difference between these two assemblies is the thickness of the overlay layer. A 92% increase in overlay layer thickness led to a 67% increase in minimum radius of curvature for these specific systems. Therefore, the thicknesses of the sheathing layers have a large impact on the predicted curvature of the overall floor system.

Curvature of Joists

The deflection of joists has often been pointed to as the primary cause of tile cracking and grout failure. Yet, at this time, there is no ceramic tile test that addresses the impact of joist deflection on expected tile floor performance. For this reason, the minimum radius of curvature of joists that would be applicable to the TCA recommended assemblies were calculated for comparison with the sheathing system values. No. 2 2x10 Southern Pine members were assumed as the floor joist members. The maximum span length was calculated using a deflection limit of L/360 under live load only. Table 2 shows the minimum radius of curvature at the center span of the floor joists.

Table 2. *Minimum radius of curvature at center span of floor joist when the joist span is limited by a live load deflection of L/360.*

Live Load	Dead Load	Joist Spacing	w_{LL}	E	I	L_{max}	w_{TL}	M_{max}	ρ_{min}
(psf)	(psf)	(in)	(lb/in)	(psi)	(in^4)	(ft)	(lb/in)	(in-lb)	(in)
40	10	16	4.44	1,600,000	98.93	16.4	5.56	26,839	5,898
40	10	19.2	5.33	1,600,000	98.93	15.4	6.67	28,521	5,550
40	10	24	6.67	1,600,000	98.93	14.3	8.33	30,723	5,152

The radius of curvature values are approximately 10 times greater than the radius of curvature values for the plywood systems, and thus the predicted curvature of the joists is only 10% of the predicted sheathing curvature. These values were calculated assuming independent curvatures between the joists and the plywood assembly.

Conclusions

The current method of designing ceramic tile floor assemblies based on deflections may not be the best or most reliable approach. Ceramic tile is a brittle material that cannot withstand significant bending stresses. A design procedure based on curvature, rather than deflection, could provide a more accurate and representative response to actual applied loads.

The predicted curvature of the joists used in these assemblies is approximately 10% of the predicted curvature of the sheathing systems. This fact suggests the possibility that limiting the curvature of the plywood assembly by design may help prevent tile cracking and grout problems in residential applications.

In cooperation with the Terrazzo, Tile and Marble Association of Canada (TTMAC), we are currently planning tests at TTMAC (Ontario, CN) to validate our curvature theory as it relates to tile floor performance predicted by the ASTM C627 test. We will be utilizing the new Universal Tester developed by TTMAC cooperators and designed by Tool Development, Inc., Newmarket, Ontario. Among several unique features, the design allows for the inclusion of full size joists and their deflection behavior as part of the ASTM C627 test. Two tests will be conducted with identical tile installations, except in one case the joists will be designed to the L/360 live load deflection limit, and in the second case, the joists will be designed to the L/720 deflection limit.

Based on our proposed theory, we do not expect differences in test results based on ASTM C627 test criteria. This experiment is expected to indicate that the sheathing and installation system should be the primary focus areas for improving tile performance at the field level. Expected test dates and other related questions can be directed to Mr. Bob Sanelli at TTMAC: bob@TTMAC.com.

References

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