Trouble under Foot - In Situ and Laboratory Investigation of Engineered Wood Flooring

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ABSTRACT
This paper presents an in situ and laboratory investigation conducted to diagnose unsatisfactory performance of new engineered wood flooring installed in an existing building. Shortly after installation, areas of flooring began to exhibit uplift and bowing (warp). Warp was more pronounced during the winter months, when indoor relative humidity was significantly below the flooring manufacturer’s stated minimum. In addition to the correlation between low humidity and warp, other possible contributing factors were also considered; these included materials, construction of the finished product, installation, and end-use conditions. The investigation included detailed documentation of floor condition, building modifications, history of reported flooring defects, and apartment occupancy; plus laboratory environmental testing. An environmental test chamber was used to expose new flooring to a range of relative humidity regimes, including the full range permitted by the flooring manufacturer (35% to 65% RH), and the lower range experienced during the winter months (as low as 15% RH). Testing and analysis confirmed that the flooring performs satisfactorily within the allowable humidity range, and that poor performance at lower relative humidity was attributable to construction layup of the flooring product, the method of installation, and the building environmental conditions.

INTRODUCTION
Finish flooring presents an array of challenges for an installation that is serviceable, durable, and beautiful. A variety of established and new products, combined with high expectations for aesthetics and durability, make design decisions more complex than in the past. This paper describes the initially unsuccessful performance of an engineered wood flooring product, presents an investigation conducted by the authors to understand key performance characteristics, and offers lessons learned for effective product evaluation and performance. The paper is divided into three sections that address the following items:

- Design and material characteristics of the engineered wood flooring product, including the type and configuration of materials used in its construction and the installation technique;
- Characteristics of the service and installation environment, including interior conditioning, concrete slab moisture emission, foot traffic, and sunlight exposure; and
- A description of the authors’ field and laboratory investigation methodologies and findings.
OVERVIEW OF SOLID AND ENGINEERED WOOD FLOORING

There are two main types of hardwood flooring – solid and engineered. Solid flooring is typically 3/4-inch thick, made of solid pieces of wood, often utilizes tongue-and-groove construction so the pieces interlock, and comes in a variety of widths, lengths, and cuts to produce desirable grain patterns. Engineered flooring was developed by the Kahrs flooring manufacturing company in Europe following WWII; it began to be widely imported to the U.S. in the 1980s. Traditionally, engineered flooring products have a face veneer wearing surface and a plywood core with a veneer back face; although newer flooring products can have medium density fiberboard or solid lumber as the core material.

Solid Wood Floors

Solid flooring can be made from any virtually wood species and can be any type of cut, commonly classified as quarter sawn, plain sawn, or rift sawn, to provide a desired appearance. Practical widths of solid strip or plank flooring are limited by material properties. One of the advantages of solid wood flooring is that, because it is cut from a solid piece of wood, it can be refinished several times with minimal loss of thickness. Solid wood flooring is not recommended for below grade applications, directly over concrete slabs, or in high moisture environments, such as kitchens and bathrooms. It is also not generally recommended for use over in-floor radiant heat systems. Some movement is to be expected with solid wood flooring due to shrinkage and swelling; gaps are typically left around the room perimeter and hidden under molding or quarter round to allow for movement throughout seasonal fluctuations in relative humidity. Solid flooring is generally nailed or stapled to a wood subfloor, usually plywood or oriented strand board. Solid wood flooring can be pre-finished or a finish can be applied following installation.

Engineered Wood Floors

Engineered flooring is a manufactured product that comes in a variety of thicknesses. It is constructed with multiple plies of wood under a wearing surface. Typically, plywood cores of engineered floors have three or more plies to produce a balanced construction to reduce warp and dimensional movement of the flooring product. The wearing surface veneer can range in thickness from less than 1/32-inch to greater than 1/4-inch thick for custom milled flooring. Engineered floors that have thick wearing surfaces can be sanded and refinished like solid wood floors. Engineered flooring materials are commonly used for installations where solid wood flooring is not recommended, such as below grade, over in floor radiant heat systems, and in areas with significant humidity fluctuations where dimensional stability is desired. Because the plies are oriented in different directions, the composite flooring is intended to be dimensionally stable. Engineered wood floors are often glued down or floated (not attached to the substrate), rather than nailed. This is an advantage when installing over in-floor radiant heat systems or over concrete slabs (with the proper underlayment). Most commonly, engineered floors are prefinished, rather than finished after installation.
Engineered Wood Floors – Floating Installation

“Floating” refers to an installation method that does not require or involve the use of staples, nails, or glue to anchor the flooring material to the floor substrate. This method is used for laminate and engineered wood floors. Solid wood floors are designed to be nailed or stapled to the substrate, and are not typically installed using the floating floor method. With floating floor installation, individual engineered flooring products designed to look like single or multiple strips or planks of flooring are attached to each other (either with glue or a snap-lock joint) but are not attached to the subfloor or underlayment on which the flooring is being installed (similar to jigsaw puzzle pieces on a table; the puzzle pieces are connected to each other but not to the table top).

Floating floors allow for slight variations of movement and expansion/contraction of the floor. Because the floor is designed to expand and contract as a unit, gaps between individual boards or planks should be minimal or non-existent. Floating floors can be installed on any level of a home, over concrete and non-traditional substrates such as other wood flooring or vinyl, and are commonly installed over in-floor radiant heat systems because there are no nails or staples that could damage the in-floor heat system, nor is there glue on the floor substrate that could fail with the heat from the in-floor radiant heat system. Floors installed via the floating method must have space around the edges of the flooring to allow for the expansion and contraction of the material. Typically, this space is concealed under base molding and/or with shoe molding/quarter round. Floating floors are generally constructed with material that is thinner and less substantial than nail-down flooring and, typically, is less expensive to purchase and install than nailed down solid hardwood floors.

Potential Problems

Both solid wood floors and engineered wood flooring have advantages and disadvantages. Solid wood flooring can exhibit cupping and gapping if not allowed to acclimate to the service conditions, or if service conditions change. Engineered wood flooring products are designed to have less in-service movement, but this is not always the case. The adhesive may fail either between the plies or between the wearing surface and the ply underneath, resulting in cupping and/or gapping or shrinking. Perhaps more significantly, although purportedly not in need of acclimatization, engineered floors can bow and cup if not manufactured properly and/or if a ply has significantly lower or higher moisture content than the other plies. Also, bowing, cupping, and gaps can develop when in-use temperature and relative humidity vary significantly from the manufactured or installation environmental conditions. It is these issues that are the focus of this paper.

BUILDING DESCRIPTION AND INITIAL PERFORMANCE

A 14-story art deco building in the Mid-Atlantic United States, originally built circa 1930, was fully renovated between 2005 and 2008 to convert it from commercial office space into luxury residential apartments. The structure of the building consists of steel framing with concrete floor slabs. It is approximately square in plan and measures approximately 100 feet on each side. The renovation included installation of new windows and new mechanical, electrical, and plumbing
systems. Heating and air conditioning is provided by a fan coils system; there was no provision for winter humidification.

Single strip engineered wood flooring was installed in numerous apartments during 2007 (Figure 1). Late that year, many of the wood floors began to exhibit various forms of distress, most notably uplift and bowing (warp). The uplift created visible and tactile springiness and flexibility in the floors, and in some cases resulted in a readily apparent upward bow (Figure 2). In addition to warp, some areas of newly installed flooring exhibited cupping, resulting in a scalloped appearance. Gaps were also apparent between flooring strips in some locations.

PRODUCT DESCRIPTION

The engineered wood flooring, which is the subject of this paper, is built from single strips that are 5 inches wide and 9/16 inches thick, with tongue and groove geometry along the edges to allow adjacent strips to lock together. Each strip is composed of three distinct layers: a 1/8-inch thick solid sawn white oak wearing (top) layer, 3/8-inch thick solid sawn cross slat pine core and 3/32-inch thick pine backing layer (Figure 3). The wearing layer is finished with ultraviolet (UV) cured acrylic urethane with aluminum oxide in base coats and anti-scratch topcoats in a satin gloss. The strips are manufactured in varying lengths from 12 inches to 84 inches.

Three methods of flooring installation were permitted per the manufacturer: nail-down, glue-down and floating. The majority of the flooring at this building was installed using the floating method. Requirements for floating installation obtained from the product literature included the following items, presented here with commentary regarding conditions in the building:

- **Dry subfloor:** Substrate conditions are critically important for any finish flooring installation. Concrete subfloors require special attention due to the hygroscopic nature of the material. Concrete emits moisture vapor indefinitely, with especially high levels in the weeks after placement, as excess mix water is released. Slab-on-grade installations typically maintain relatively high levels of moisture vapor emission indefinitely. In this installation, all floors were elevated, and the concrete was quite old. New cementitious leveling material has been installed in many locations, but a review of project records revealed that adequate cure time had been provided.

- **Installation:** Manufacturer requirements state that flooring be installed and maintained at a room temperature of 65-75°F and a relative humidity (RH) of 35-65%. These conditions should be met and maintained for at least a week before the installation. Our review indicated that in some cases relatively humidity was lower than the allowed minimum.

- **Installation Geometry:** The strips having a length of less than 8 inches should not be installed unless it is the last piece in a row. End joints should be staggered from row to row. In several instances narrow sections of flooring were installed using multiple adjacent strips of the same length. These areas were more likely to exhibit warp and uplift.
Figure 1. Overview of installed engineered wood flooring

Figure 2. Typical warping, visible at area of removed flooring
ENGINEERED WOOD FLOORING

Figure 3. Composition (layup) of a strip of the engineered wood flooring

FIELD INVESTIGATION

Engineered wood flooring was documented in 18 apartments representing a range of conditions. For each apartment, the following conditions were noted:

- **Exposure**: Location of the apartments (north, east, northeast, northwest, southeast, southwest) was noted. Among the 18 apartments we visited, 2 were located on north, 1 was on East, 5 on Northwest, 3 on Northeast, 5 on Southwest and 2 on Southeast. No strong correlation was established between sunlight exposure and flooring performance.
- **Occupancy**: Six of the eighteen documented apartments were vacant and had not been previously occupied. Occupancy changes the service condition due to increased foot traffic and increased humidity from bathing, cooking, and respiration.
- **Temperature**: Temperature in the apartments was consistently between 70 to 75 °F.
- **Relative Humidity (RH)**: RH measured in each apartment typically varied from 16% to 22% in early April, lower than the 35% minimum allowed by the manufacturer. Indoor winter humidity in colder climates is naturally quite low because air holds less total water when cooled. As an example, exterior air at 30°F, 35% RH, when warmed to 72°F, will drop to 8% RH without supplemental humidification.
- **Installation Geometry**: General observations of the installation geometry were made in each unit, including length of flooring runs, staggering of joints, and allowance for movement at the perimeter. In one unit that exhibited pronounced and widespread warp and uplift, the complete geometry of the installation was mapped, including the length and configuration of each strip.
- **Installation Technique**: Most floors were installed on the existing concrete slab using the floating technique. In some cases, portions of the apartments were constructed on elevated platforms; floors in these areas were nailed down. In other areas, flooring was
glued down to the existing concrete subfloor. Only floating floors typically exhibited distress.

- **Warping/Uplift** (Figure 3): We observed warping in most of the apartments we visited, with varying degrees of severity. In some cases, the warping was not readily visible, but resulted in visible flexing when the floor was walked on. In other cases, the warping was extensive and readily visible. The most severe warping was observed along the short flooring lengths, such as the area between the kitchen counter and table, and hallways.

- **Cupping** (Figure 4): Cupping occurs when the edges of the flooring strips lift relative to the center, create a scalloped effect when viewed across multiple installed flooring strips. Cupping was observed in several units, but was typically minor and consistent with behavior exhibited under low relative humidity conditions.

![Figure 4. Cupping](image)

- **Gaps**: Scattered edge gaps (along the length of flooring strips) and scattered butt gaps (at the ends of strips) were observed in a few apartments. Nearly all gaps observed were 1/16 inch or less, within a normal range for wood flooring in low humidity conditions.

- **Delamination, Splits, Checks**: We did not observe any delamination, splits or checks.

- **Wood Moisture Content**: Using a capacitance moisture meter, moisture content in the flooring was measured to range between 8% and 14%.

- **Perimeter Conditions**: Floor baseboards at various locations in one of the apartments had been removed and hence the ends of the flooring strips where they meet the walls were exposed. We observed that the ends of the floorings were free to move, and the space between the flooring strip ends and the wall varied between 5/32 inch and ½ inch.

**Laboratory investigation**

We obtained two unopened boxes of flooring, each of which contained an identical inventory of 5-inch wide flooring strips stacked in 6 layers (Figure 5). Each box yielded 11 test specimens 30 inches long. Each specimen was assigned a unique identification code that identified the box, layer, and flooring strip from which it was cut.

In addition to the environmental test specimens, we obtained 2-inch long drying samples after discarding the first 2 inches from the end of the strips (to eliminate end drying effects). The
samples were shrink-wrapped to retain moisture and tested for moisture content measurement via oven drying.

Specimens were divided into three test groups with 10, 6, and 6 specimens in Groups A, B, and C, respectively, in order of introduction into the test chamber. After the initial measurements were taken, specimens were shrink-wrapped to preserve moisture content prior to introduction to the environmental chamber. Each group contained equal numbers of specimens from Box 1 and Box 2.

The test specimens were laid flat, in the same orientation as they would normally be installed. Temperature was maintained at (71.6°F) throughout testing, because temperature readings at the building were fairly consistent, and to limit the number of variables being tested. Test specimens from Groups A, B, and C were introduced to the chamber sequentially at different humidity set points, to model and evaluate a variety of installation and service conditions with a simple test program utilizing a single environmental chamber. The test protocol was as follows:

- Specimens in Group A were placed in chamber at 35% RH, and allowed to acclimate over several days.
- Specimens in Group B were added and the humidity lowered to 25% RH. All specimens in the chamber were allowed to acclimate over a period of several days. RH was then lowered to 15%.
- Specimens in Group C were added to the chamber and RH was raised to 35%. All three groups of specimens were now in the chamber and were allowed to acclimate.
- The humidity was increased to 65% RH and specimens were allowed to acclimate.

Prior to the testing and periodically during the testing described, we measured the weight of each specimen to monitor moisture loss (or gain), and to monitor when the specimens were approaching equilibrium with each of the test environments created in the chamber. Once the weight of the specimens stabilized the next phase of testing was begun. We measured the deflection and width of the specimens between the phases. Deflection was measured relative to a straight edge at five-inch increments along the length of each specimen, with the specimen laid on edge to eliminate the effects of gravity on the measurement. We defined the maximum allowable vertical deflection (warp) as 1/360 of the length of the flooring strip, usually stated as L/360. This criterion was based on standard building code allowances for allowable floor slab deflection for live load, and correlated to a maximum permissible deflection of 0.083 inch (slightly less than 1/10 inch) along the length of a 30-inch sample.
Most specimens exhibited substantially increased deflection when the humidity was lowered to 15% RH. This is consistent with site observations of significantly greater observed lifting as interior RH dropped during the cooler months. However, as the specimens acclimated to the 15% RH environment, many of the samples recovered, and four flattened out sufficiently to fall within the L/360 criteria. Figure 6 shows aggregated laboratory results for RH at 35%, 25%, and 15%. Note that performance relative to the L/360 criterion was satisfactory until RH dropped below 25%. This is consistent with the manufacturer’s stated criteria.

Figure 6. Aggregated laboratory results for one box of flooring. Blue lines denote L/360 deflection envelope; vertical scale magnified 10x for clarity.
CONCLUSIONS AND RECOMMENDATIONS

Warping was most common at short runs and free edges of longer runs. While limited and isolated areas of warping/lifting were observed in the field of longer runs, this condition was much less common. Little force was required to flatten a warped strip. Accordingly, a limited number of flooring strips with warping tendency can be held mostly flat if surrounded by and connected to strips that lay flat. Staggered installation geometry, with consistently offset end joints, should further contribute to membrane action that controls warping of isolated individual strips. Over longer flooring runs, the self-weight and continuity of the flooring tend to limit warping and uplift. At shorter runs, none of these factors that tend to control warping and uplift are present. Only the edges are restrained by connection to other members, and the ends are free to retract in response to warping, allowing uplift.

Based on our findings, we determined that the single strip engineered hardwood flooring product is suitable for use within the range of environmental conditions recommended by the manufacturer. The predominant cause of the observed distress of the flooring was the lack of winter humidification in the building. Other reported performance concerns— including cupping and gapping – were generally minor and consistent with expected behavior of any wood flooring product.

We recommended that supplemental humidification be installed in all apartments with the engineered wood flooring. We also recommended future flooring installation be glue-down or nail-down due to the resistance to warping these methods offer through positive attachment to the slab. These recommendations were successfully implemented.