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NOTE

Prediction of early age curling in thin concrete topping over wood floor systems

Peter Lee, Ying H. Chui, Ian Smith, Noel Mailvaganam, and Gerry Pernica

Abstract: This paper presents finite element simulations of curling of unreinforced concrete topping laid over wood floor systems. The finite analysis consists of two parts. The first part calculates the relative moisture distribution with respect to the age of the concrete, while the second determines the topping curling deformation based on modulus of elasticity, density, and shrinkage of the concrete. With the finite element model the curling profile at any point in time can be predicted. Predictions agree reasonably well with measurements from a full-sized wood floor with a thin concrete topping. A model-based parametric study was performed. For the floor size investigated the results of the parametric study indicate that curling is greatly influenced by topping thickness and relative humidity of the surrounding air. Although the modelling as discussed is a preliminary approach, it provides a basis for further enhancements that will address factors such as creep and relaxation of concrete and deformation of the underlying floor system.

Key words: finite element analysis, concrete topping, wood floor, curling, shrinkage.

Résumé : Cet article présente des simulations par éléments finis de l'ondulation d'une surface de béton non-renforcé étendue sur un système de plancher de bois. L'analyse par éléments finis consiste en deux parties. La première partie calcule la distribution de l'humidité relative en fonction de l'âge du béton, tandis que la deuxième détermine l'ondulation de la surface basée sur le module d'élasticité, la densité et le rétrécissement du béton. En utilisant le modèle d'éléments finis, le profil d'ondulation peut être prédit à tout instant. Les prédictions concordent relativement bien avec les mesures provenant d'un plancher de bois grandeur nature avec une mince surface de béton. Une étude paramétrique basée sur le modèle a été produite. Pour la grandeur de plancher étudiée, les résultats de l'étude paramétrique démontrent que l'ondulation est grandement influencée par l'épaisseur de la surface et l'humidité relative de l'air environnant. Bien que la modélisation telle que discutée n'est qu'une approche préliminaire, elle procure une base pour des améliorations futures qui considéreront des facteurs tels que le fluage et la relaxation du béton de même que la déformation du système de plancher sous-jacent.

Mots clés : analyse par éléments finis, surface de béton, plancher de bois, ondulation, rétrécissement.

[Traduit par la Rédaction]

Introduction

In recent years it has become popular to use a thin layer of unreinforced concrete topping as a sound barrier over wood floors consisting of a sub-floor and wood joists. During drying concrete near the surface dries and shrinks earlier

than the core concrete, causing high tensile stress and possible cracking at the surface. In addition, because the topping is not attached to the supporting sub-floor, it curls up around the edges, as a result of a gradient in moisture content, temperature, and elastic modulus through the thickness. This curling can cause excessive localized vibration near the edges. Few studies on this issue have been reported. Chui and Smith (1997) reported an average corner uplift of about 5 mm for a 28-day-old, 38-mm-thick unreinforced concrete topping, under laboratory conditions. The floor area was 4.47 m × 3.6 m. For 1.9 m × 3 m wood-concrete composite strip floors tested by Ennis (2001) a 38-mm concrete topping curled by about 6 mm at the corners.

The work reported in this paper is part of a research project aimed at developing design and construction guidelines for light-frame wood floor systems overlaid with a thin unreinforced concrete topping. The objective of the work described herein is to develop a model based on finite element analysis that predicts edge curling in topping from strain induced by the movement of moisture within concrete. The

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model can then be used to study how curling in thin unreinforced topping is affected by various construction and concrete variables.

Modelling of curling in concrete topping

Curling occurs primarily as a result of differential shrinkage through the thickness of concrete over time, which is in turn controlled by the moisture gradient through thickness. The curling deformation at any given point in time is a function of the rigidity of the concrete at that time. Therefore, the rate of development of concrete modulus also plays a major role in determining the extent of the curling.

In this study the prediction of curling in concrete topping on wood-based sub-floor is achieved by using a commercial finite element package, ANSYS (ANSYS 1996). A two-step modelling approach is adopted here. First, a moisture diffusion model is assembled in ANSYS using the heat conduction analogy as described below to calculate the moisture gradient. In part two, the model is reassembled using solid mechanics elements in ANSYS to calculate the shrinkage deformation, hence the curling of concrete topping.

The element suitable for the diffusion analogy analysis in ANSYS is the three-dimensional SOLID70 Thermal Solid with a thermal conduction capability (ANSYS 1996). Once the moisture gradient has been computed, the model is reassembled using the ANSYS structural solid element (SOLID45). During this structural analysis part, the results of the moisture distribution from the diffusion model are superimposed onto the element nodes as moisture loading. The shrinkage coefficients with respect to the age of the concrete topping are calculated according to the shrinkage model recommended by ACI 209R-92 for regular concrete (ACI 1997). Once the shrinkage coefficients are determined, the structural model calculates the deformations generated by the moisture profile in the topping. The effect of the self-weight of concrete, which counteracts upward curling, is included in the analysis.

A key issue of this modelling approach affecting the accuracy of the prediction is the ability of the model to accurately predict moisture gradient in concrete. Moisture transfer within concrete during drying is influenced primarily by the diffusion process, which is greatly influenced by the water content, porosity, and the relative humidity of the surrounding medium. In the ANSYS package, moisture diffusion modelling capability is not available. However, because of the similarity between the principles of moisture diffusion and heat conduction, the theory of thermal expansion and contraction due to temperature change can be applied to model swelling and shrinkage due to moisture change. In thermal analysis the cooling process of an arbitrary body yields the following heat flux equation:

$$[1] \quad \frac{\partial T}{\partial t} = \nabla \left(\frac{k}{\rho c} \nabla T \right)$$

where T is temperature, t is time, and the term $k/\rho c$ is known as thermal diffusivity and is defined as thermal conductivity, k , divided by the product of density and specific heat, ρc . In eq. [1], if T is replaced by R , the relative humidity, and $k/\rho c$ by D , the diffusion coefficient for moisture, it is transformed

into the classical differential equation for one-dimensional moisture diffusion. The values for the parameter D and R are estimated using the empirical method proposed by Akita et al. (1997) such that

$$[2] \quad \frac{D}{D_1} = \frac{1}{[29(1 - R/100) + 1]^{1.4}}$$

$$[3] \quad R = a_1 + a_2 H + a_3 \gamma + a_4 H^2 + a_5 H \gamma + a_6 \gamma^2 + a_7 H^3 + a_8 H^2 \gamma + a_9 H \gamma^2$$

where D_1 is the value of D (mm^2/d) when R is 100%, H is the relative humidity (%), γ is the water-cement ratio of concrete, and a_1 to a_9 are constants. From an experimental study Akita et al. (1997) found the following values for the constants in the diffusion equation: $a_1 = 33.4$, $a_2 = 1.46$, $a_3 = -28.7$, $a_4 = -1.58 \times 10^{-2}$, $a_5 = -1.45$, $a_6 = 4.22$, $a_7 = 7.73 \times 10^{-5}$, $a_8 = 1.74 \times 10^{-2}$, and $a_9 = -4.22 \times 10^{-2}$.

Assessment of validity of proposed modelling approach

To assess the validity of the proposed modelling approach using ANSYS, a 38-mm thick by 7.92 m by 7.62 m concrete topping was modelled and the prediction compared with experimental measurements. This concrete topping was placed over an oriented strand board (OSB) sub-floor of a wood floor system tested in the laboratory. Concrete specimens were sampled and tested at specific time intervals for the determination of material properties such as relative moisture content, density, and elastic modulus.

The concrete topping was cured in an uncontrolled environment with an average relative humidity of about 50% and temperature within the range of 5–10°C. In addition to monitoring the concrete curling, the concrete relative humidity through thickness was measured using a moisture probe. Using these measurements, a profile of the relative moisture content through the thickness of the concrete topping was obtained. The measured moisture profile at 7, 14, 21, and 28 d is compared with the predicted results for the 38-mm-thick topping, as shown in Fig. 1. The discrepancies between model prediction and the experimental data may be due to the non-steady state of the ambient environment. Despite these uncertainties and the complexity of the problem being investigated in this study, the predicted moisture profile appears reasonable when compared with the measured response. The model predicted a corner uplift of 3.6 mm, which compared favourably with the measured value of 4 mm.

Parametric study

In an effort to understand the factors that affect the curling of a thin unreinforced concrete topping, a parametric study was undertaken. The concrete mix had a specified compressive strength of 30 MPa, and was used in the 7.92 m $\times$ 7.62 m test floor discussed above. The mix proportion, curing time, and ambient relative humidity were used as a basis to derive input into the model for shrinkage prediction.

Fig. 1. Model prediction of moisture profiles versus measured values.

Topping plane area

Three different topping sizes, kept at a constant relative humidity of 50%, were simulated. The length and thickness of the concrete topping were kept constant at 7.62 m and 38 mm, respectively, while its width was varied (4.28, 7.92, and 15.24 m). In this study the concrete topping was assumed to be moist cured for 1 d. The calculated corner uplift values at 28 d are given in Table 1. The results indicate that, despite the significant size difference among these three toppings, the 38-mm-thick concrete topping resulted in similar magnitude in curling after 28 d. While the topping plane areas investigated appear to have a marginal effect on the magnitude of corner uplift, the analysis does reveal that shrinkage increases as the plane dimension increases. Curling is not sensitive to topping plane area is likely because of the counteracting effect of the self-weight of the concrete near a floor corner.

Topping thickness

To investigate the effect of topping thickness on corner uplift, a range of topping thicknesses from 25 to 300 mm was simulated. The topping plane area was kept constant at 7.92 m $\times$ 7.62 m, and the concrete was assumed to moist cure for 1 d. The simulated results are plotted in Fig. 2, which shows that corner uplift increases rapidly as the topping thickness increases up to 100 mm, thereafter it reduces as thickness increases. While the results confirm the various findings and recommendations (CPCA 1991) that increasing thickness results in smaller curling for concrete slabs thicker than 100 mm, they also reveal an opposite trend for toppings with thickness less than 100 mm.

The occurrence of a peak curling value when topping thickness is varied over a broad range is expected. This is because for thin topping curling increases with topping thickness as the moisture gradient becomes more pronounced. However, as thickness increases, the topping becomes more rigid, and as the topping thickness reaches a certain value, its rigidity and self-weight start to dominate

Table 1. The effects of concrete topping plane dimensions on corner uplift.

Concrete topping dimensions	Thickness (mm)	Corner uplift (mm)
4.28 m $\times$ 7.62 m	38	3.58
7.92 m $\times$ 7.62 m	38	3.59
15.24 m $\times$ 7.62 m	38	3.59

over moisture gradient. As a result, above this thickness value curling decreases.

For the application that is of interest here, i.e., thin concrete topping over wood floor system, it seems that corner uplift at floor edges can be minimized by reducing the thickness of the topping and by the requirement on the size of the aggregate. For shrinkage control, CSA Standard A23.1-M90 (CSA 1990) recommends that aggregate about one-third the thickness of the topping be used. This means, for example, that shrinkage of the 50-mm topping can be reduced by using larger aggregates in the concrete. A typical mix with 19-mm aggregates will have a sand to total aggregate ratio of about 0.42. Further reduction of sand content can be achieved by introducing intermediate-sized aggregates to the mix. Additional simulation results presented in Table 2 show how curling can be reduced by using maximum-sized aggregate and reducing the sand content. To meet the CSA Standard A23.1-M90 aggregate size requirement, it seems that 38 mm is an optimum topping thickness, since aggregate size of less than 10 mm is not readily available. This topping thickness happens to be the most common thickness found in wood floor construction.

Ambient environment

With decreasing ambient relative humidity the surface moisture content of the concrete topping decreases. The sensitivity of curling to changes in relative humidity of the ambient surrounding was studied using the developed model. The concrete topping was assumed to be moist cured for 1 d

Fig. 2. Effects of concrete topping thickness on corner uplift. **Table 2.** The effects of sand content on corner uplift at 50% relative humidity in air.

Sand content	Thickness (mm)	Corner uplift (mm)
45.6% with 12 mm aggregate	50	5.75
42.2% with 19 mm aggregate	50	5.27
30% with 19 mm and intermediate aggregate	50	3.40

Table 3. Effects of ambient environment on corner uplift.

Thickness (mm)	Corner uplift (mm)		
	30% relative humidity	40% relative humidity	50% relative humidity
25	2.75	2.13	1.41
38	8.06	6.08	3.59
50	13.67	10.11	5.75

and then exposed to 30, 40, and 50% relative humidity. The plane dimensions of the topping were kept at 7.92 m $\times$ 7.62 m. Three topping thicknesses were studied. The results are given in Table 3. The 50-mm-thick topping exhibited large corner uplift at 30 and 40% relative humidity. However, results presented in Table 2 indicate that uplift for thin topping can be reduced by using larger aggregates and less sand. The analyses showed that shrinkage is very sensitive to relative humidity. It should be of no surprise that thicker topping, within the range of 38–50 mm, is more susceptible to curling when exposed to dry conditions. A drier surface and thicker topping will lead to a steeper moisture gradient and cause greater uplift at the corners.

Compressive strength

Concrete strength has an indirect influence on concrete curling, since it affects modulus and shrinkage properties. In this study each simulated specified strength value was

Table 4. Effects of compressive strength on corner uplift.

Specified compressive strength (MPa)	Corner uplift (mm)
15	2.36
20	2.80
25	3.27
30	3.66
35	4.06

achieved by adjusting the cementitious material and sand content according to the Absolute Volume Method (CPCA 1991) while keeping the water content and coarse aggregate content constant. The analysis results presented in Table 4 indicate that higher strength concrete produces a topping with larger curling. This is primarily because any improvement in compressive strength also leads to higher shrinkage, caused by the adjustment in the cement and sand contents. Therefore, to minimize curling low strength concrete is preferred.

Conclusions

By using a thermal conductivity analogue to model the moisture diffusion behaviour through concrete, curling of thin unreinforced concrete topping can be predicted with reasonable accuracy. Based on a numerical parametric study, it is observed for typical concrete topping placed over wood floor systems that

- floor area has little effect on the magnitude of concrete topping curling
- for thin concrete toppings, decreasing thickness of the topping reduces the amount of curling
- reducing sand content with intermediate aggregates reduces curling
- high relative humidity in surrounding air during curing reduces curling

It should be noted that the finite element model used here accounts for only drying shrinkage. Enhancements are desirable for accuracy and to account for factors such as shrinkage due to water loss during the hydration process, creep and relaxation behaviour of concrete and wood floor elements, and deflection of the wood floor itself.

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