A simple method for estimating transient heat transfer in slab-on-ground floors

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Abstract

The problem of calculating transient heat transfer in concrete floor slabs is complicated due to ground coupling, which can require the numerical solution of two or three-dimensional transient conduction equations. This paper presents a simplified method for calculating transient slab-on-ground heat transfer that can be incorporated within hourly simulation programs. The method assumes that there are two primary one-dimensional paths for heat transfer from a ground-coupled floor slab: (1) one-dimensional heat transfer from the perimeter of the slab to the ambient and (2) one-dimensional heat transfer between the slab interior surface and a portion of the soil beneath the slab. The perimeter heat transfer is assumed to occur at quasi-steady state and is characterized in terms of a perimeter heat loss factor ($F_p$). Transient heat transfer within the slab and ground are modeled using a simple thermal circuit employing three nodes with an adiabatic boundary condition at a specified depth within the soil underneath the slab. Although some simulation models consider this type of two-path model, there appears to be no validation of this approach and there is no guidance for specifying perimeter heat loss factors and underfloor soil depths and node locations for the thermal circuit. In the current paper, results from detailed two-dimensional finite-element models for typical floor constructions and soil properties were used to identify (1) locations for nodes within the slab and soil, (2) correlations for soil depth as a function of soil properties associated with the underfloor adiabatic boundary condition, and (3) correlations for perimeter heat loss factor as a function of soil properties and edge insulation levels for different constructions. Transient heat transfer results from the simple model compared well with results from the finite-element program for different floor constructions, edge insulation, soil properties, locations, and times of year.

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1. Introduction

Ground-coupled heat transfer through concrete floor slabs is typically a significant component of the total load for heating or cooling in low-rise buildings like residential buildings, etc. It was estimated that earth-contact heat loss accounted for about 10% of the annual heat loss for average homes in the US during the early 1970s [1]. Since that time, buildings have been constructed with more insulation, better windows, and more air tight envelopes. As a result, buildings are generally more energy efficient today and ground-coupled heat loss may account for 30–50% of the total heat loss for a well-built house [1–3]. Furthermore, transients associated with floor slabs can be very significant and important to consider in estimating both peak loads for sizing of equipment and total energy requirements for economic analyses. Recently, there has been considerable interest in utilizing energy storage within floor slabs and other building materials to achieve load shifting and reduction in on-peak cooling requirements and costs (e.g., [4]). The load shifting is accomplished simply by manipulating zone setpoint temperatures over time within the comfort zone. The motivation for the work presented in this paper was the need for a simple model for predicting transient heat transfer in ground-coupled...
floor slabs that could be integrated within an hourly simulation program and used to assess the potential for load shifting opportunities associated with building energy storage in small commercial buildings.

There are well-established models for steady-state, ground-coupled heat transfer from basements and slab floors. For instance, ASHRAE [5] presents a steady-state model for heat loss from ground-coupled floor slabs that are typically used for modeling in residential applications. The model assumes that the predominant path for heat loss from the slab occurs between the slab perimeter and the ambient. The floor heat transfer is characterized in terms of a perimeter heat loss factor (Fp). ASHRAE gives typical values of Fp for a limited number of foundation insulation configurations and climatic conditions. The model and heat loss factors were developed from measurements conducted for specific foundation sizes and soil properties under steady-state heat transfer conditions. No general approach has been presented for estimating perimeter heat loss factors from material and soil properties. EN ISO 13370 [6] presents a similar method for estimating steady-state ground floor heat flux. Medved and Cerne [7] used this general formulation and developed simplified method to calculate parameters of the model for different sizes and shapes of buildings with and without basements with a variety of properties.

Krarti et al. [8] developed the ITPE (Interzone Temperature Profile Estimation) method that combines analytical and numerical techniques to obtain two- and three-dimensional solutions of the heat conduction equation for slab-on-grade floors and basements [9]. The ITPE method provides a general solution for the temperature field within soil under steady conditions for a slab-on-grade and slab-on-ground floor. The ITPE formalism has been applied to develop a simplified method for seasonal foundation heat loss [10], evaluate the thermal bridge effects of floor foundation [11], optimize insulation R-value by life-cycle cost analysis [12,13] and develop simplified tool for the calculation of foundation heat gain [12,13].

For analyzing the use of building thermal mass, it is very important to consider transient heat transfer within the floor slab and underfloor materials [14]. One approach involves solution of two- or three-dimensional transient conduction equations using finite-difference or finite-element methods. The solution generally requires the numerical solution of a large number of coupled equations. Because of the computation required, studies have been performed to develop fast computational schemes or modeling simplifications for this problem. For instance, Seem et al. [15] developed a method for calculating transfer functions in multi-dimensional conduction heat transfer problems that is useful for
modeling ground-coupled floor slabs. The approach utilizes the following steps: (1) convert a finite-difference representation of the partial differential equations to a state-space formation, (2) utilize the analytical solution to the state-space formation with a ramp or step input to determine a transfer function representation, (3) utilize model-order-reduction techniques to obtain a simplified transfer function representation. The transfer function representation is determined prior to or at the beginning of a simulation and is then used at each timestep to calculate energy flows at the boundaries of the domain (e.g., at the floor-interior interface). For annual simulations, the transfer function representation requires much less computation than that associated with numerical solutions to the partial differential equations at each timestep.

Adjali et al. [16] performed numerical simulations for a ground-coupled floor slab and compared predictions with measurements. Two- and three-dimensional conductive heat transfer models based on a finite-volume method for the floor and soil were added to APACHE, a whole building thermal simulation program widely used in Europe. In-situ measurements were made at the Cardiff School of Engineering, University of Wales, over a period of 18 months. Temperatures (internal and external air, at different depths in the slab and the soil down to 4 m beneath the floor surface), heat fluxes through the concrete floor slab, the thermal conductivity of the ground and the water table and soil moisture content were measured. The results showed that the purely conductive earth-contact model accurately predicted the thermal behavior beneath the building. A two-dimensional analysis was found to be adequate. Three-dimensional effects were only important near the corners of the slab.

Even with simplifications, the computational requirements for solving two or three-dimensional heat transfer within floor slabs and ground soil is very significant. Simulation tools available for estimating cooling and heating loads in commercial and residential buildings typically do not employ detailed multi-dimensional models for ground-coupled heat transfer. For instance, TRNSYS [17] considers one-dimensional transient conduction in the floor and materials immediately beneath the floor. A portion of the soil can be considered with a specified underfloor boundary condition. However, no guidance is given for the amount of soil to be included and the temperature of underfloor boundary condition to employ.

Some simulation models (e.g., [18]) consider two paths for heat transfer from a ground-coupled slab floor: (1) steady-state heat loss from the perimeter to the ambient and (2) one-dimensional transient conduction in the floor and materials immediately beneath the floor with an adiabatic underfloor boundary condition. However, no literature could be found that validates this modeling approach. Furthermore, it’s not obvious how to specify perimeter heat loss factors and underfloor soil depths and the number and location of nodes for the simplified thermal circuit.

The current paper starts with the general two-path modeling approach for transient slab heat transfer and develops heuristics and correlations for general application of the method. In particular, results from detailed two-dimensional finite-element models for typical floor constructions and soil properties were used to identify (1) locations for nodes within the slab and soil, (2) correlations for soil depth as a function of soil properties associated with the underfloor adiabatic boundary condition, and (3) correlations for perimeter heat loss factor as a function of soil properties and edge insulation levels for different constructions.

2. Methodology

2.1. Case study descriptions

A number of ground-coupled floor slabs were considered in the model development and evaluation study. The basic geometry and some of the parameters are shown in Fig. 1. The finite-element modeling was applied to a two-dimensional slice including the slab floor and surrounding soil. The construction and dimensions are typical of a small commercial building. Many of the results were determined using a slab length.

![Fig. 1. Schematic of the slab-on-ground geometry.](image)
of 20 m. It was determined that the spatially averaged heat flux at the indoor floor surface is insensitive to slab length for values greater than about 10 m. The dimensions of the soil (depth of 10 m and width of 50 m) were chosen so that the bottom and side boundaries were nearly adiabatic corresponding to the ‘far field’ assumption [16]. Due to symmetry, only half of the floor and soil shown in Fig. 1 was modeled. The internal zone boundary condition was convection to a zone temperature that varies within a relatively narrow range. The boundary condition at the soil surface considered both convection and radiation using an equivalent sol–air temperature [5]. Typical convective heat transfer coefficients and a solar surface absorptance for summer conditions were specified for the upper surfaces of the floor and ground. Two widely used constructions were selected for floor slabs from the Builder’s Foundation Handbook [19]. Configuration A used a 15 cm (6 in) heavy weight concrete slab laying directly on ground soil. Configuration B had a 10 cm (4 in) heavy weight concrete slab with 4 in of sand and pea gravel above the ground soil. A heavy weight concrete foundation (20 cm in width and 1 m in depth) with various foundation insulation levels was considered.

For a given floor construction and set of boundary conditions, the primary factors that affect slab heat flux are the level of insulation on the foundation and the soil properties. If insulation is employed on the foundation, then typically about 1 in (2.54 cm) to 2 in (5.1 cm) of styrofoam is attached to the outer foundation wall below ground. In this study, outer foundation insulation was assumed to extend from the top surface of the ground to a 1 m depth. Base case results were determined for insulation having a thermal resistance corresponding to 1 in (2.54 cm) of styrofoam insulation ($R = 0.95 \text{ K} - \text{m}^2/\text{Wor}R = 5.4 \text{ ft}^2\text{-}^{\circ}\text{F} - \text{h}/\text{Btu}$). A range of different insulation levels were considered ($R = 1.425 \text{ K} - \text{m}^2/\text{W}, R = 0.95 \text{ K} - \text{m}^2/\text{W}, R = 0.475 \text{ K} - \text{m}^2/\text{Wand} R = 0 \text{ K} - \text{m}^2/\text{W}$) in developing correlations for perimeter heat loss factors.

Table 1 gives thermal properties of floor, underfloor materials, and soil used for base case results. Soil properties can vary considerably according to soil type and moisture content. It is extremely difficult to consider the time dependence of soil properties due to changes in moisture content. Typically, average properties are assumed for a particular site. The base case soil properties in Table 1 are representative of saturated soil of medium sand with fine gravel [20]. In addition, soil properties were varied over a wide range to develop correlations for perimeter heat loss and soil depth for the simplified model.

For steady-state conduction, the only soil property of interest is the thermal conductivity. For transient conduction problems, thermal diffusivity (ratio of thermal conductivity to the product of the density and specific heat) is the relevant parameter. Thermal diffusivity, $\alpha$, is a measure of the ability of the material to diffuse thermal energy through conduction. The higher the thermal diffusivity the faster a material will respond to changes in the boundary conditions. In addition to the base case, soil thermal conductivity was varied in the range of 0.6–3.5 W/m-K. This corresponds to thermal diffusivities in the range of 2.99 E-6–1.74E-6 m$^2$/s.

For the simulation cases considered in this study, the zone and ambient sol–air temperature boundary conditions were varied using 24-h periodic functions of the following form.

$$T(t) = A_0 + A_1 \sin \left( \frac{\pi}{12} t + \phi_1 \right) + A_2 \sin \left( \frac{\pi}{6} t + \phi_2 \right) + A_3 \sin \left( \frac{\pi}{3} t + \phi_3 \right).$$

For the ambient sol–air temperatures, different sets of coefficients were determined through regression using hourly weather data from different locations and different times of year. Hourly ambient temperatures and horizontal radiation were used along with the solar absorptance and convection heat transfer coefficient given in Fig. 1 to compute sol-air temperatures for the different cases. For instance, Fig. 2a shows a sample 24-h variation in sol-air temperature for Arcata, CA (California climate zone 1) on August 1st based on TMY2 data. The zone temperature variation was chosen based upon typical results associated with conventional night setup control in small commercial buildings [14], as shown in Fig. 2b. In this study, Fig. 2a and b were used as the base case to build the correlations only. Ambient sol–air temperatures and zone temperatures for small commercial buildings from other locations in different seasons under various controls were used in validating the model.

### 2.2. Finite-element model

A commercially available finite-element program [21] was employed to solve the two-dimensional transient heat conduction problem for the geometry shown in Fig. 1. The slab floor slab and surrounding soil, footer and concrete wall structure were modeled using approximately 3000 nodes. Fig. 3 depicts the non-uniform mesh arrangement employed. The element sizes were smaller in areas of larger temperature gradients, such as near the top surface and at the edge of the floor.
slab. Adiabatic boundary conditions were specified at 15 m from the edge of the slab and at a depth of 10 m from the top surface. The internal zone (slab and wall) and ground surfaces were subjected to convective heat transfer using the boundary conditions described in the previous section.

For the transient modeling, the initial temperatures of the floor slab and soil directly beneath the slab were chosen as the average of the zone air temperatures over the 24-h period. The initial temperatures of the surrounding soil were determined using the model of Baggs given in Eq. (2) [22], which was developed for naturally occurring ground temperatures away from building structures.

\[
T(y, t) = T_m - 1.07 k_v A_s \exp(-0.00031552 y^{0.5}) \cos \left( \frac{2\pi}{365} (t - t_0 + 0.018335 y^{0.5}) \right),
\]

(2)

where the vegetation shade factor, \( k_v \), was taken to be 1.0 for bare ground like a parking lot or side walk outside a retail store.

A 1-h time step was used for all simulations. The model was run for many identical days in a row until the solution approached a steady-periodic condition. This required simulation lengths of up to 12 000 h.

2.3. Simplified ground-coupled floor modeling

For estimating zone cooling and heating loads, the quantity of interest for modeling a ground-coupled floor is the heat transfer rate at the top surface of the floor. The simplified modeling approach considers two primary one-dimensional paths for heat transfer from a ground-coupled floor slab: (1) one-dimensional steady-state heat transfer from the perimeter of the slab to the ambient and (2) one-dimensional transient heat transfer between the slab interior surface and a portion of the soil beneath the slab. At any time \( t \), the total heat transfer rate from the zone air to the floor is determined as

\[
\dot{Q}_t = F_p P (\bar{T}_z - \bar{T}_{sol-air}) + A_f q_{00}^f
\]

(3)

where \( F_p \) is the slab perimeter heat loss factor, \( P \) is the slab perimeter, \( \bar{T}_z \) and \( \bar{T}_{sol-air} \) are 24-h average zone and sol-air temperatures (updated continuously), \( A_f \) is the total floor surface area, and \( q_{00}^f \) is the heat flux (heat transfer rate per unit area) at the floor surface for a one-dimensional transient analysis. The one-dimensional heat flux is essentially the heat flux that occurs at

![Fig. 3. Schematic of the two-dimensional finite-element modeling mesh.](image-url)
the centerline of the slab (i.e., the left-most boundary of Fig. 3).

The one-dimensional transient analysis uses a simple thermal circuit employing 3 nodes with an adiabatic boundary condition at a specified depth within the soil underneath the slab as depicted in Fig. 4. The number and location of the nodes was determined through analysis of and comparisons with finite-element modeling results. The resulting model can be represented with three continuous, linear, time-invariant differential equations as:

\[
\begin{align*}
C_1 \frac{dT_1}{dt} &= \frac{T_2 - T_1}{R_1} + \frac{T_3 - T_1}{R_2} \\
C_2 \frac{dT_2}{dt} &= \frac{T_1 - T_2}{R_2} + \frac{T_3 - T_2}{R_3} \\
C_3 \frac{dT_3}{dt} &= \frac{T_2 - T_3}{R_3} + \frac{T_g - T_3}{R_4}
\end{align*}
\]

(4)

The three differential equations can be put in matrix form as

\[
\begin{bmatrix}
\frac{dT_1}{dt} \\
\frac{dT_2}{dt} \\
\frac{dT_3}{dt}
\end{bmatrix} =
\begin{bmatrix}
-\frac{1}{R_1C_1} & -\frac{1}{R_2C_1} & 0 \\
\frac{1}{R_2C_2} & -\frac{1}{R_2C_2} & \frac{1}{R_2C_2} \\
0 & \frac{1}{R_3C_3} & -\frac{1}{R_3C_3}
\end{bmatrix}
\begin{bmatrix}
T_1 \\
T_2 \\
T_3
\end{bmatrix}
= \begin{bmatrix}
T_f \\
0 \\
0
\end{bmatrix}.
\]

(5)

Eq. (5) is a state-space representation for the simplified one-dimensional conduction heat transfer problem. It is solved analytically and converted to a transfer function using the method of Seem et al. [15]. The transfer function solution gives the current one-dimensional heat flux at the floor surface in terms of current and past hourly values of the zone temperature and past hourly values of the heat flux.

\[
q_{f,t}'' = s_0 T_{f,t} + s_1 T_{f,t-1} + s_2 T_{f,t-2} + s_3 T_{f,t-3} + e_1 q''_{f,t-1} + e_2 q''_{f,t-2} + e_3 q''_{f,t-3}.
\]

(6)

The \(s\) and \(e\) transfer function coefficients are determined from the solution to the state-space problem with linear changes in zone temperature over each hour as outlined by Seem et al. [15]. The transfer function representation is determined prior to a simulation and is then used at each hourly timestep to calculate the floor heat transfer.

The initial temperatures of the floor slab and soil directly beneath the slab were chosen as the average of the zone air temperatures over the 24-h period. A 1-h time step was used for all cases and the model was run to a steady-periodic condition for each day type considered.

2.4. Process for correlating perimeter heat loss factor and soil depth

In order to apply the simple model described in the last section, it is necessary to specify a perimeter heat loss factor and depth of soil under the floor. The perimeter heat loss depends on the floor construction, amount of foundation insulation, and soil properties. The appropriate depth of soil to include in the analysis depends on the floor materials and soil properties. Results from finite-element modeling were used to develop correlations for these two parameters. The following steps were followed to develop and evaluate the correlations and simplified model.

1. The finite-element model was used to generate one-dimensional heat fluxes at the adiabatic center line of the floor slab (i.e., the left-most boundary in Fig. 3) for floor configurations A and B with different soil properties and the baseline ambient and zone temperature variations.
2. A simplified one-dimensional transient model was also developed for each configuration and soil type in terms of the unknown soil depth.
3. For a given floor configuration and soil properties, errors in predictions of hourly centerline floor surface heat fluxes were minimized with respect to soil depth.
for the simplified model. The problem involved minimizing the following cost function:

\[ J = \sqrt{\frac{1}{24} \sum_{t=1}^{24} \left( q''_{CTF,t} - q''_{FE,t} \right)^2} \] (7)

with respect to the soil depth, \( D \), where \( q''_{CTF,t} \) was determined from the simplified model and \( q''_{FE,t} \) was from the finite-element model.

4. Correlations of optimized soil depth \( D \) in terms of soil conductivity, \( k \), were developed for estimating centerline floor heat transfer.

5. The two-dimensional finite-element model was used to generate transient heat transfer results over the entire domain depicted in Fig. 3 for floor configurations A and B with different soil properties and the baseline ambient and zone temperature variations. The total heat transfer rates at the top floor surface were determined for each hour from the two-dimensional results.

6. For a given floor configuration, foundation insulation, and soil properties, errors in predictions of hourly floor surface heat transfer rates were minimized with respect to the perimeter heat loss factor for the simplified model. The problem involved minimizing the following cost function:

\[ J = \sqrt{\frac{1}{24} \sum_{t=1}^{24} \left( \dot{Q}_{t} - \dot{Q}_{FE,t} \right)^2} \] (8)

with respect to perimeter heat loss factor, \( F_p \).

7. Correlations of optimized perimeter heat loss factor in terms of soil conductivity and foundation insulation \( R \) value were developed for the different floor configurations.

8. Predictions from the resulting simplified model were compared with two-dimensional finite-element modeling results for a range of ambient conditions (winter and summer in different locations), indoor temperature variations, soil conductivities, and foundation insulation levels.

3. Results and discussion

3.1. Floor configuration A: 4" heavy-weight concrete on soil

Fig. 5 gives an example of the effect of soil depth on the performance of the simplified one-dimensional heat flux model (Fig. 4a) for a soil thermal conductivity of 1.73 w/m-K. The optimal soil depth to use in this simplified model is about 45 cm for this case. Fig. 6 compares the centerline heat flux determined with the one-dimensional finite-element model and simplified model with the optimized soil depth.

Optimized soil depths for a range of soil thermal conductivities were determined and used to develop a correlation. For floors without gravel below the slab (Configuration A), the resulting correlation is

\[ D^* = -0.0489 k^* + 0.5692 k^* + 0.4709, \] (9)

where \( k^* \) is the ratio of the thermal conductivity to the baseline thermal conductivity of 1.73 w/m-K and \( D^* \) is the ratio of the soil depth to the soil depth associated with the baseline conductivity (45 cm). Fig. 7 shows comparisons between the curve fit and optimized soil depths.

The overall simplified model utilizes the simplified centerline heat flux model with the soil depth correlation and an edge heat loss model as given in Eq. (3). Errors between model predictions from Eq. (3) and two-dimensional finite-element results were minimized to obtain perimeter heat loss factors for various edge insulation levels and soil conductivities. Fig. 8 gives an example of hourly comparisons for average floor surface heat flux obtained using an optimized soil depth and perimeter heat loss factor for baseline parameters and conditions. The simplified model is able to accurately characterize the transient heat transfer at the floor surface.
The perimeter heat loss factor depends strongly on the edge insulation and soil conductivity and weakly on the dimensions of the zone. Fig. 9 shows the effect of dimensionless soil conductivity and half-floor length (distance from centerline to edge) on the optimized perimeter heat loss factor for baseline parameters and conditions, except with no foundation insulation. Without edge insulation, the impact of floor length is negligible for overall floor lengths greater than about 10 m. Adding edge insulation leads to even lower impact of the zone dimension on edge heat loss. Therefore, it is reasonable to neglect the effect of zone dimensions on edge heat loss for most buildings.

Fig. 9 indicates that perimeter heat loss factor is linear with soil conductivity. However, it also depends upon the edge insulation. The following correlation was developed for floor configuration A using two-dimensional finite-element results for the baseline geometry and conditions over a range of soil conductivities and edge insulation levels.

\[ F_p = ak^* + b, \]  

(10)

where the slope \( a \) and intercept \( b \) are correlated as

\[ a = -0.1935R^3 + 0.4594R^2 - 0.5029R^* + 1.4911, \]

\[ b = -0.6539R^3 + 1.5876R^2 - 1.4163R^* + 0.5628, \]

and where \( R^* \) is the ratio of the edge insulation R-value to the base case edge insulation \( R = 0.95 \text{ W/m}^2\text{-K} \).

Fig. 10 shows comparisons between the optimized perimeter heat loss factors and values determined from the correlation of Eq. (10).

### 3.2. Floor configuration B: 10 cm (4 in) HWC slab with 4 inches of gravel

Optimized soil depths for a range of soil thermal conductivities were determined for configuration B (Fig. 5b) and used to develop the correlation in Eq. (11). Fig. 11 shows comparisons between the curve fit and optimized soil depths.

\[ D^* = -0.1106k^2 + 0.7305k^* + 0.3809. \]  

(11)

For floor configuration B, the linear form given in Eq. (10) was used to correlate perimeter heat loss factor
with soil conductivity and edge insulation. The resulting expressions for the slope \(a\) and intercept \(b\) in Eq. (10) are

\[
a = -0.118 R^3 + 0.3928 R^2 - 0.4419 R^* + 1.4463,
\]

\[
b = -0.2937 R^3 + 1.0164 R^2 - 1.2702 R^* + 0.5897.
\]

**Fig. 12** shows comparisons between the optimized perimeter heat loss factors and values determined from the correlation of Eq. (10).

### 3.3. Validation

The correlations were developed using a single profile for ambient temperature variations with an associated deep ground temperature that were representative of summer in California and a single profile for zone temperature variation that was associated with night ventilation precooling. However, the resulting model was tested over a wide range of ambient and zone temperature conditions, including summer and winter conditions in a variety of locations. **Fig. 13** shows example results in New York City in summer (August 1st) under night-ventilation control for floor configuration A. **Fig. 14** gives results in Chicago for winter (February 1st) with conventional night setup control for floor configuration B. These results are typical of the accuracy of the simplified model in predicting slab heat transfer rate as compared with the finite-element results. Part of the explanation for the good agreement between the simplified model and the numerical simulations is the fact that the correlations for the simplified model were developed using the same software and assumptions used for the validation. Agreement with measurements would not be expected to be as good because of un-modeled effects, such as time variation in soil moisture content.

### 4. Conclusions

A simple model was developed for ground-coupled concrete floor slabs that can predict spatially averaged transient heat flux at the interior surface and could be integrated with existing building load simulation tools. The model incorporates correlations for the effects of ground soil properties and edge insulation that were
developed for two common floor configurations. Hourly heat flux predictions compared very well with predictions from a two-dimensional finite-element program for these two geometries.

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