{ TC "'CHAPTER TWO: SLAB LOSS MODELS'" \l 1 }CHAPTER

TWO

SLAB LOSS MODELS

Both of the buildings in this study had slab-on-grade foundations. They were constructed of 4 inches of concrete over a granular fill (sand) base. Heat loss through these slabs proved to be a significant part of the heating load in winter months. This was particularly true for the one-story retail building.

The multizone building component in TRNSYS models slab foundations as a special case of the zone walls. Usually a constant temperature is specified for the boundary of the slab, and then the heat loss through the slab is found to this boundary.

A constant-temperature boundary was not a valid method in this study for two reasons. First, the method did not provide good agreement between the energy use in the two buildings and that calculated by the models. One cannot determine *a priori* the best temperature at which to set the boundary because the temperature of the ground beneath the slab depends on the heat loss through the slab and the temperature of the ground surrounding the building. A constant-temperature boundary was also inadequate to model the effects of building standards on the performance of the building envelope. One of the changes mandated by ASHRAE Standard 90.1 is that, in some climates, additional insulation must be installed around the perimeter of the building. To model the effect of this insulation requires a detailed model, capable of estimating the effect of the added insulation on the loads in the interior of the building.

2.1 Finite Element Models{ TC "2.1 Finite Element Models" \l 2 }

A finite element model was used to more accurately model the heat loss through the slabs in the two commercial buildings. Finite Element Heat Transfer (FEHT), is a computer program developed at the University of Wisconsin - Madison to numerically model transient heat transfer in two-dimensional conduction problems (Klein, 1992). FEHT approximates a solid as a group of nodes formed into triangular elements. It uses numerical iteration to solve the general conduction heat transfer equation in a solid:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\dot{q}-\rho c\frac{\partial T}{\partial t}=0 \tag{2.1}$$

A two-dimensional, scale model was created to calculate the heat transfer in the slabs of the two buildings. A separate model was created for each level of perimeter insulation at each location. Figure 2.1 shows the general arrangement of the finite-element models. Each one used more than 160 nodes to represent the concrete slab, granular fill, perimeter insulation and surrounding soil.

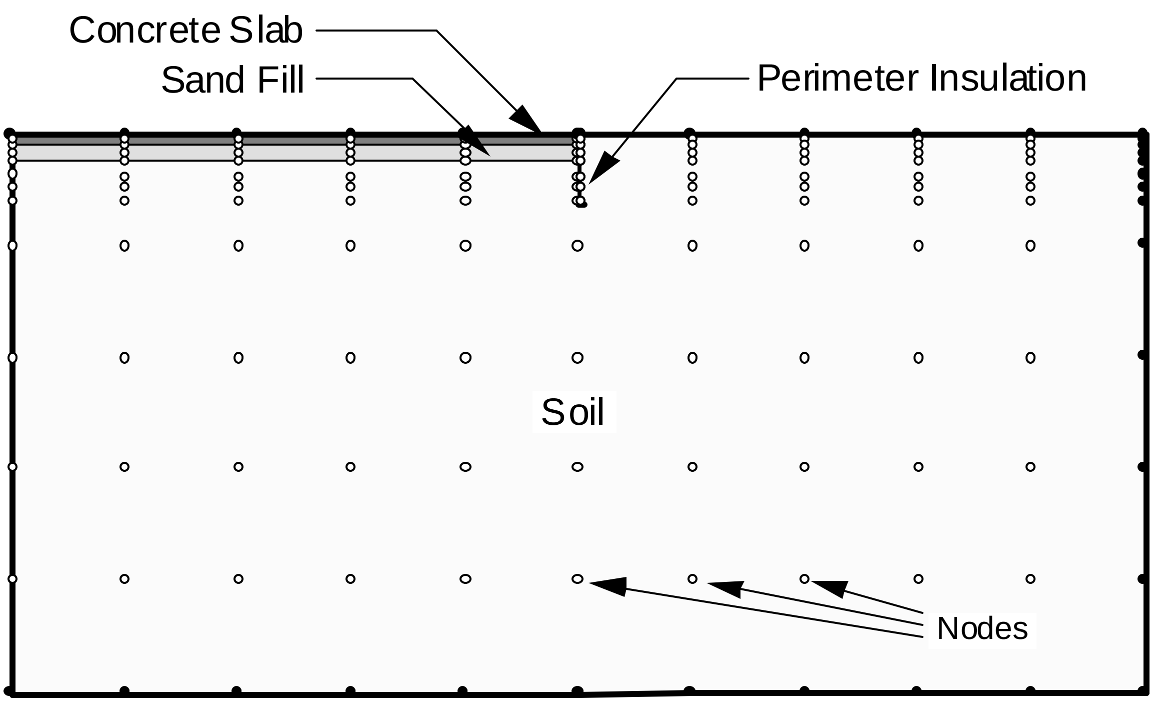

Figure 2.1 Schematic of finite element model{ TC "Figure 2.1 Schematic of finite element model" \l 5 } (to scale).

A prototype section was modeled for each slab configuration. Only the outer 5 m of the slab was included in the model. It was found that the heat loss through the slab declined to a constant value at regions closer to the interior of the slab. Therefore the value of the heat loss in the slab interior was taken to be that at 5m from the perimeter.

A number of boundary conditions were needed for the FEHT model. The temperature of the top of the slab, inside the building, was assumed to be a constant 20 C. The vertical edge of the model beneath the building was assumed to be an adiabatic boundary. The horizontal boundary at the bottom of the model was assumed to be at a constant temperature. For each building location, this temperature was set to the annual average air temperature for the site. This assumption was also used by Krarti (1989, 1992, 1994) in various studies of heat loss in basements and slabs. The boundary condition assumptions are summarized in Figure 2.2.

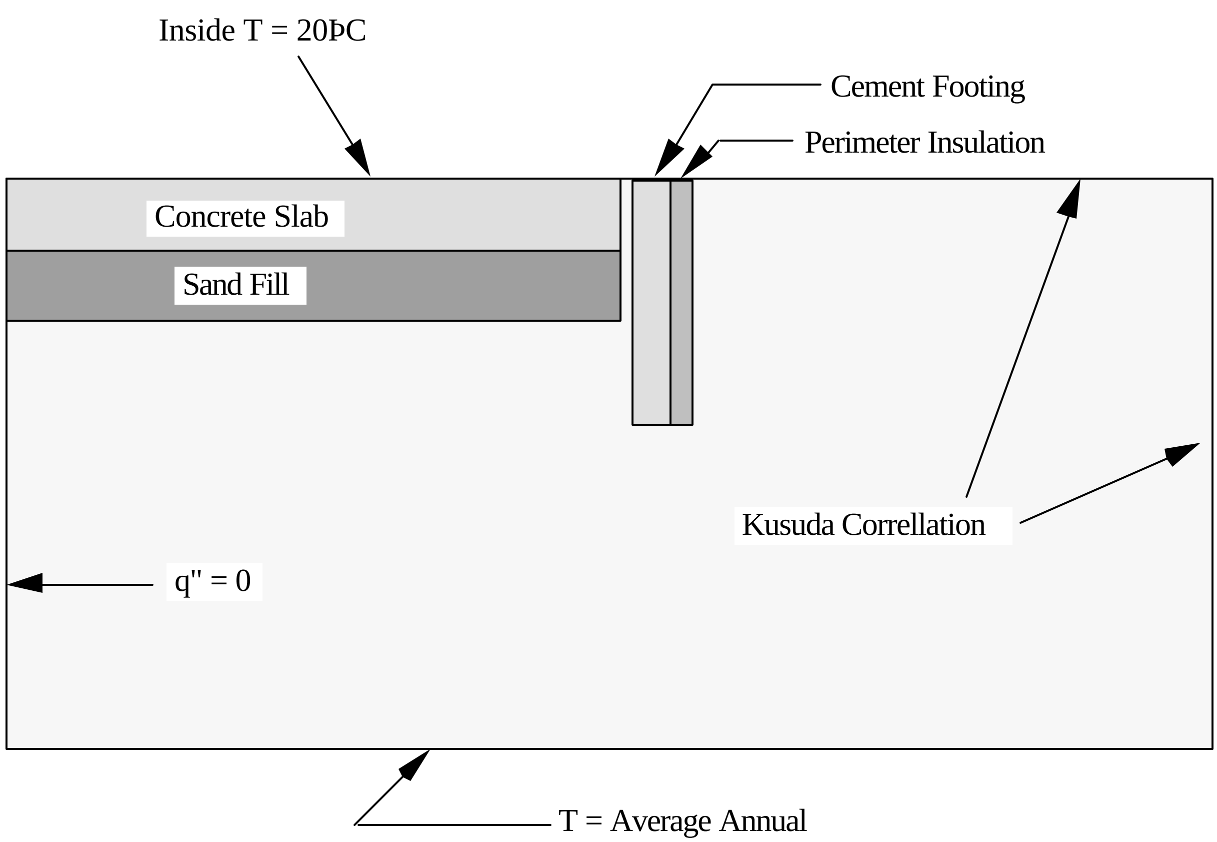

Figure 2.2 Boundary conditions for finite element slab model{ TC "Figure 2.2 Boundary conditions for finite element slab model" \l 5 } (not to scale).

A further boundary condition was needed for the temperature of the soil at the vertical boundary far from the building slab (the farfield temperature). A function relating soil temperature for undisturbed earth, and depth, over the course of a year was developed by Kusuda and Archenbach (Kusuda, 1965):

$$T(Z_{depth}, t_{year}) = T_{mean} - T_{amp} * \exp\left\{ -Z_{depth} \left(\frac{\pi}{365 * \alpha_{soil}} \right)^{1/2} \right\}$$
$$* \cos\left\{ \frac{2\pi}{365} \left[t_{year} - t_{shift} - \frac{Z_{depth}}{2} \left(\frac{365}{\pi \alpha_{soil}} \right)^{1/2} \right] \right\} \quad (2.2)$$

where:

T_{mean} = Mean value of ground surface temperature over year

T_{amp} = Amplitude of surface temperature variation

α_{soil} = Thermal diffusivity of soil

t_{shift} = Time lag between beginning of year and time of minimum surface temperature

The Kusuda correlation gives a sinusoidal variation in ground temperature about a mean value. The amplitude of the variation decreases with depth at a rate that depends on the properties of the soil. The time shift term accounts for the difference between the minimum temperature and the beginning of the calendar year.

The slab model was repeated for five different locations around the U.S.. Kusuda's original paper gives values for the mean temperature, amplitude and time shift for many locations around the country. The values used in this study are summarized in Table 2.1 below.

	T mean [C]	T amp [C]	T shift [days]	α_{soil} [m^2/s]
Madison Wi	8.5	15.0	36	6.45E-07
Phoenix Az[1]	21.7	11.1	35	6.97E-07
Washington DC[2]	14.1	13.9	35	1.01E-06
Miami Fl[3]	25.0	6.1	37	6.45E-07
Seattle Wa	12.2	8.9	35	3.35E-07

1 - Diffusivity for Tempe Az.
2 - Data from Marlboro Md.
3 - Tamp & Tshift from Gainesville Fl.

Table 2.1 Soil properties for the Kusuda correlation at five locations.**{** TC "Table 2.1 Soil properties for the Kusuda correlation at five locations." \l 6 **}**

The soil was modeled to a depth of 5 m and up to 5 m away from the edge of the slab in each case. At a depth of 5 m, the Kusuda correlation yields a temperature very close to the average mean value. According to the finite element models, at 5 m away from the edge of the slab, the heat loss from the slab has diminished to a negligible value. Therefore it seems that these are reasonable boundaries for the analysis. Krarti set similar limits in his analyses (Krarti 1989, 1992, 1994).

The level of perimeter insulation in the model was varied for each location. In Phoenix and Miami no perimeter insulation is required by Standard 90.1, so the slabs were modeled without it. For each of the remaining cities the slab was modeled up to and exceeding the level of insulation required by the code. The models were run using properties for expanded polystyrene (EPS) insulation at thicknesses of 1, 1.5 and 3 inches, corresponding to R values of 5, 7.5 and 15 hr-ft^2-F/Btu (0.9, 1.3 and 2.6 m^2-K/W).

The finite element models were run for each configuration of insulation level and location. From the model results, the heat loss was calculated at each 1 m section of the slab, from the perimeter to the interior of the slab. Time steps of 48 hours were used over the course of the year, with heat losses interpolated linearly between time steps.

The heat losses through the slab were then scaled to the dimensions of each zone in the building models.

$$\dot{q}_{slab} = \sum_{i=1}^{N} \dot{q}_{slab,i} * A_i \qquad (2.3)$$

where:

$\dot{q}_{slab}$ = Total heat loss through slab in zone

$\dot{q}_{slab,i}$ = Heat loss through 1 m segment i

A_i = Area in zone corresponding to segment i

N = Total number of 1 m segments (N = 5)

To find the heat loss for a particular zone, the perimeter area in the zone was multiplied by the heat loss for the 1m segment at the perimeter, plus the area from 1 m to 2 m from the perimeter multiplied by the heat loss for that segment, and so on for each of the 5 segments modeled in the finite element analysis. The fifth segment corresponded to the remaining interior region in the center of the zone.

2.2 Results of Slab Modeling{ TC "2.2 Results of Slab Modeling" \l 2 }

The heat loss through the building slab varies with distance from the building perimeter. Figure 2.3 shows how these losses varied for Madison Wisconsin with 1 inch thick, two feet deep, vertical EPS insulation. The heat loss shows the greatest value and fluctuation near the building perimeter, with loads at the center of the building remaining nearly constant.

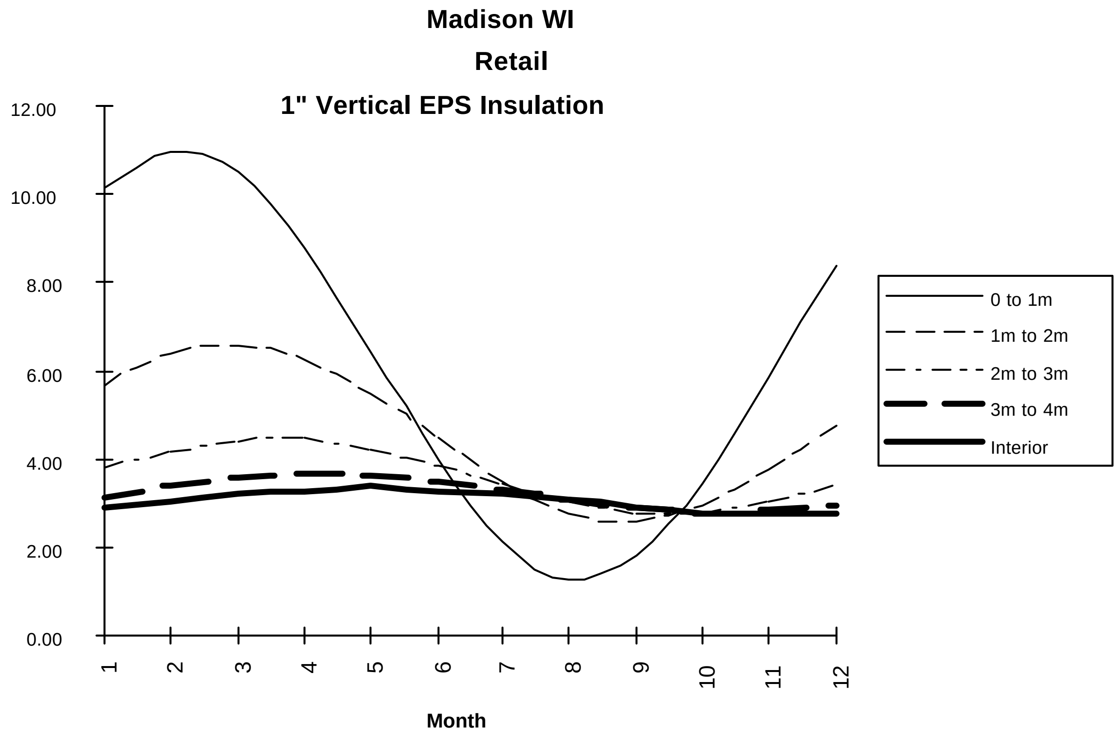

Figure 2.3 Slab heat loss for Madison Wisconsin{ TC "Figure 2.3 Slab heat loss for Madison Wisconsin" \l 5 } - varying distance from slab perimeter with 1 inch thick vertical insulation to two feet deep.

These losses were scaled to reflect the shapes of the slabs in the two buildings. The overall weighted average heat loss from the slabs from the retail and office buildings are shown in Figures 2.4 and 2.5 respectively. The slab losses from the office building were slightly higher than those of the retail building because the building has a higher aspect ratio. The office building has a longer, thinner plan, and therefore has a higher fraction of its total floor space closer to the perimeter of the building.

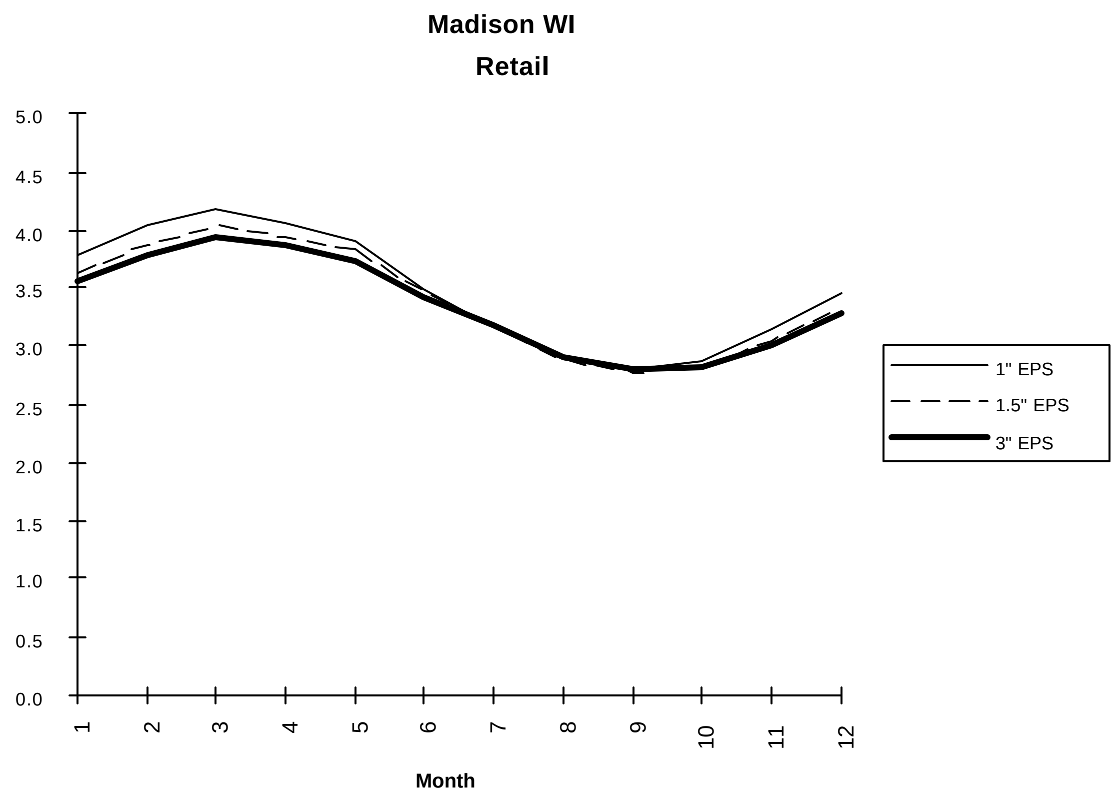

Figure 2.4 Slab heat loss for Madison Wisconsin retail building{ TC "Figure 2.4 Slab heat loss for Madison Wisconsin retail building" \l 5 }
for varying insulation thickness.

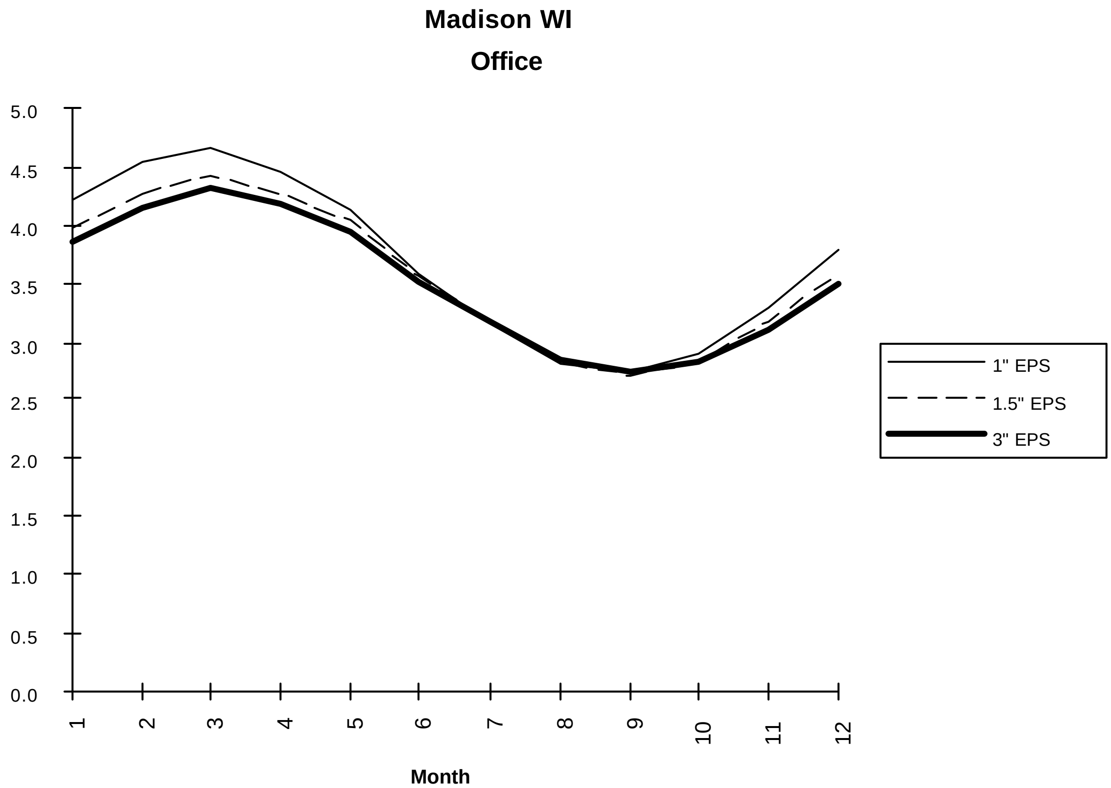

Figure 2.5 Slab heat loss for Madison Wisconsin office building{ TC "Figure 2.5 Slab heat loss for Madison Wisconsin office building" \l 5 }
for varying insulation thickness.

In Madison, there is a greater change in the heat loss in going from 1" to 1.5" EPS than from 1.5" to 3.0" EPS. This trend is apparent for both the retail and office building. It indicates the effect of diminishing returns as more insulation is added to the perimeter of a building. The question of what level of perimeter insulation is optimal will be addressed in a later section.

The slab losses are plotted for the two building in the Seattle, Washington, location in Figures 2.6 and 2.7 The heat loss through the slabs in Seattle are much lower than those in Madison due to the generally milder climate.

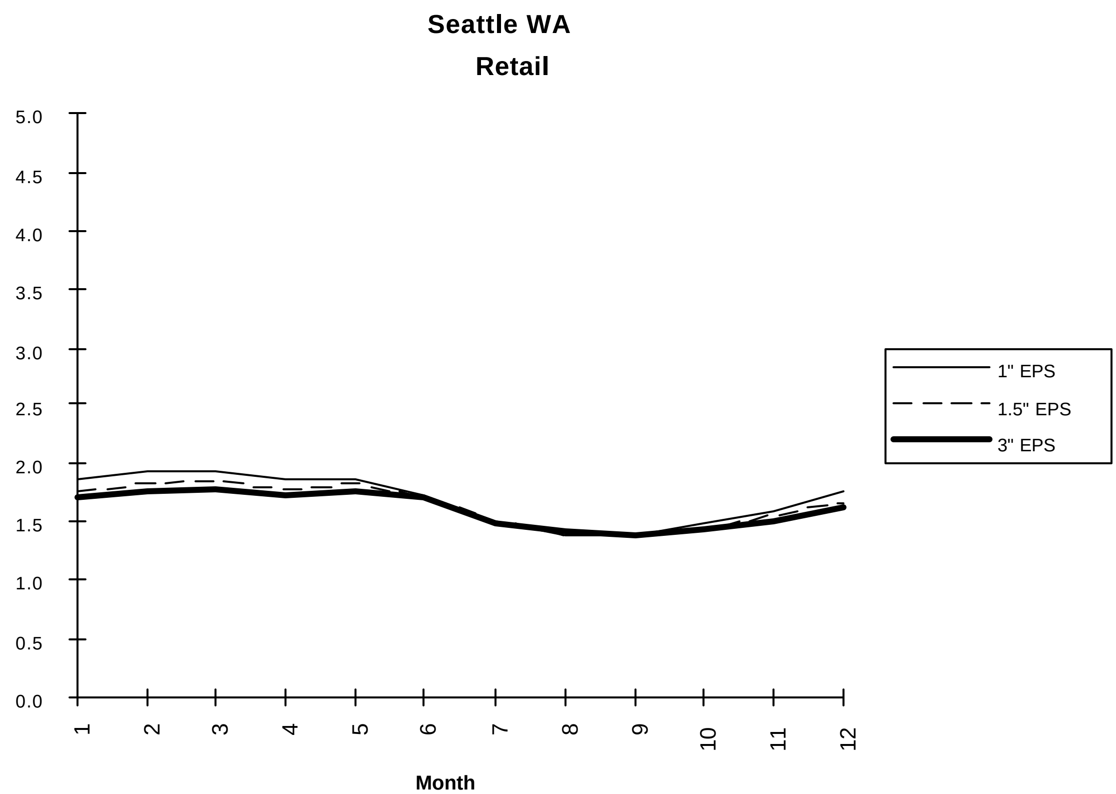

Figure 2.6 Slab heat loss for Seattle Washington retail building**{** TC "Figure 2.6 Slab heat loss for Seattle Washington retail building" \l 5 **}** for varying insulation thickness.

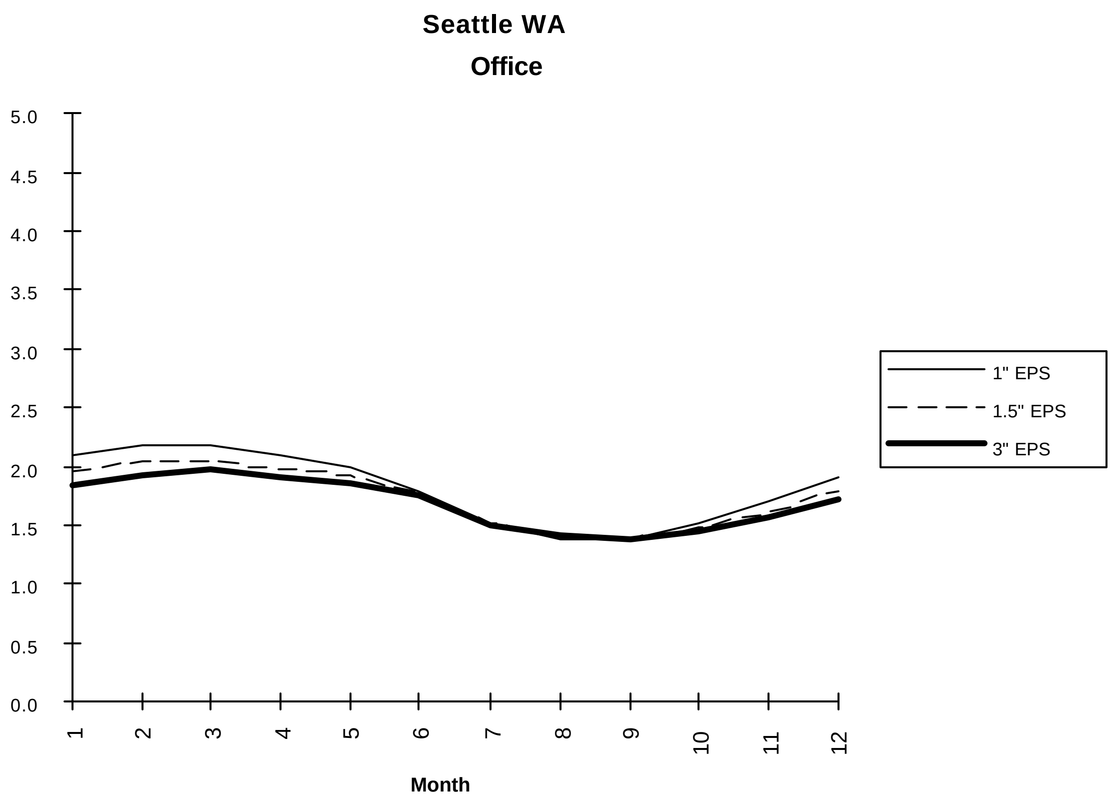

Figure 2.7 Slab heat loss for Seattle Washington office building{ TC "Figure 2.7 Slab heat loss for Seattle Washington office building" \l 5 }
for varying insulation thickness.

The slab heat losses for Washington, DC, are shown in Figures 2.8 and 2.9. The slab losses in Washington show a much greater variability because the amplitude of the surface ground temperature fluctuation is high (13.9 C). This causes the difference between indoor and outdoor temperatures to vary widely over the course of the year. Therefore the heat loss to the ground also varies widely.

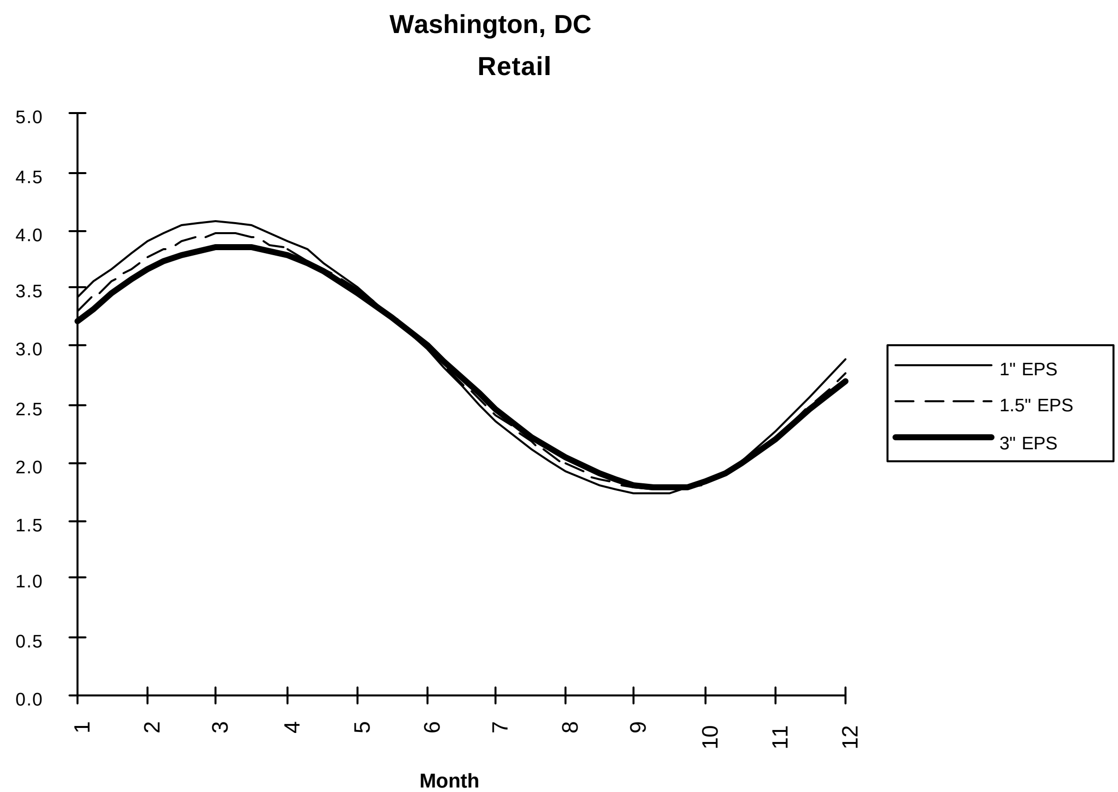

Figure 2.8 Slab heat loss for Washington DC retail building{ TC "Figure 2.8 Slab heat loss for Washington DC retail building" \l 5 }
for varying insulation thickness.

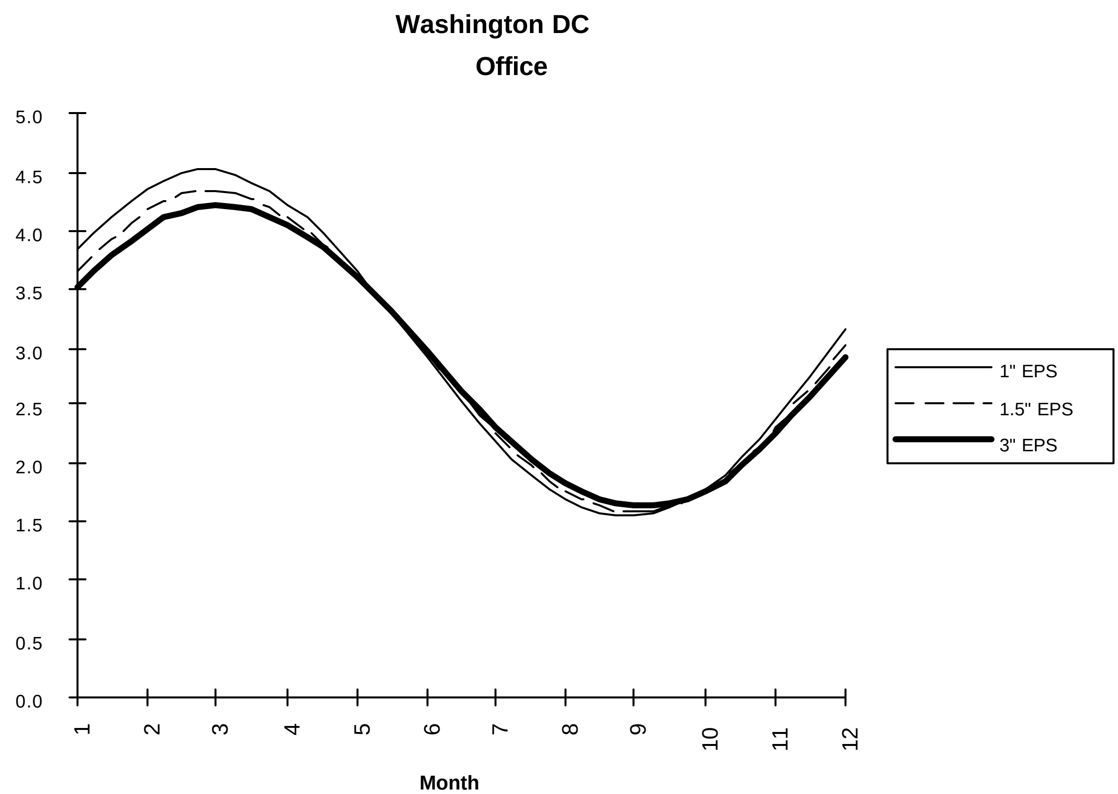

Figure 2.9 Slab heat loss for Washington DC office building{ TC "Figure 2.9 Slab heat loss for Washington DC office building" \l 5 }
for varying insulation thickness.

ASHRAE Standard 90.1 establishes criteria for perimeter insulation in different climate regions in the U.S.. Figures 2.10 and 2.11 show the slab heat losses for the retail and office buildings respectively, in five locations. The plotted value reflects the case where the perimeter insulation level meets the requirements of the ASHRAE standard. Details of the code compliance are addressed in a later section.

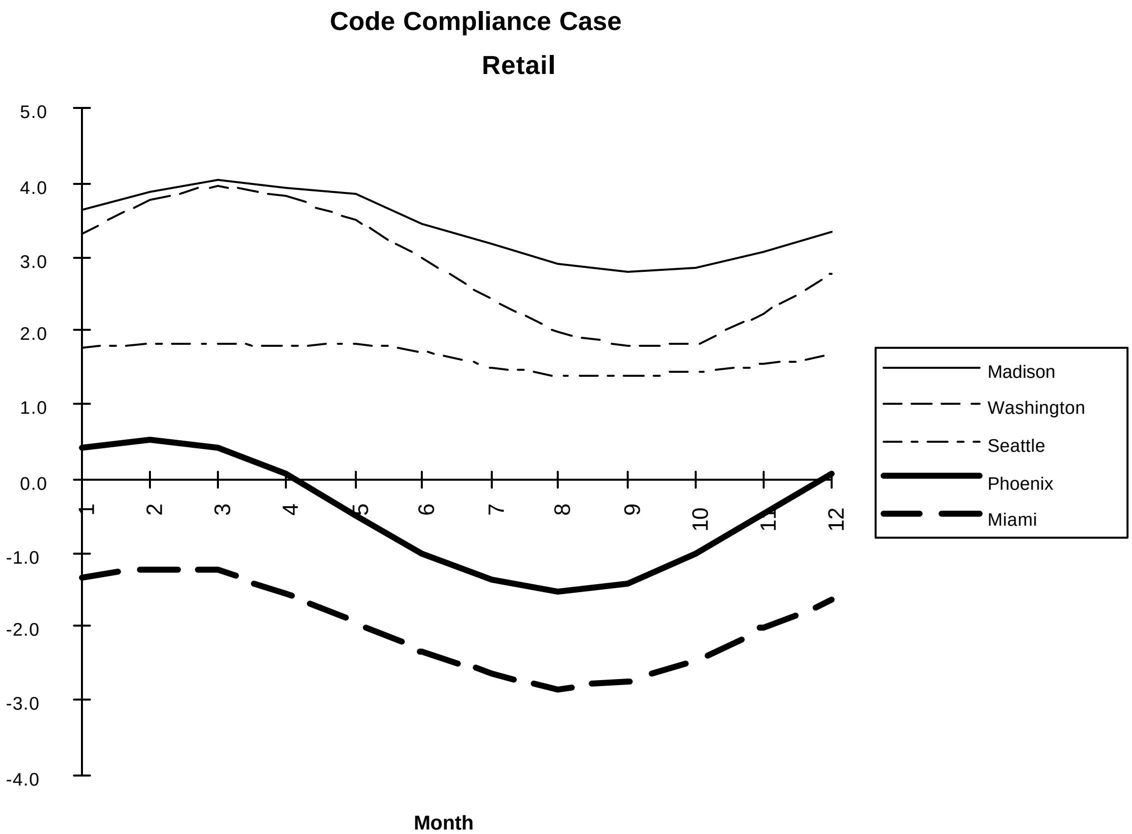

Figure 2.10 Slab heat loss for retail building in five locations.**{** TC "Figure 2.10 Slab heat loss for retail building in five locations." \l 5 **}**
All comply with ASHRAE Standard 90.1

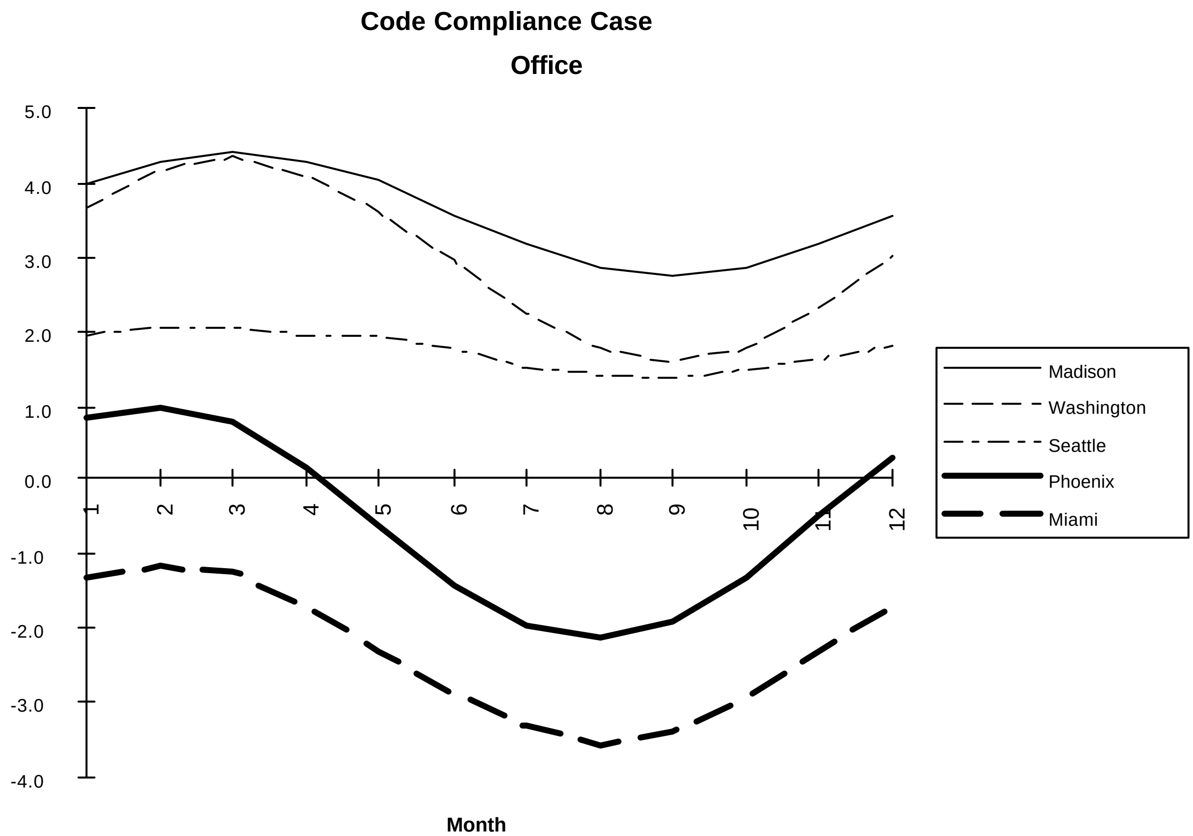

Figure 2.11 Slab heat loss for office building in five locations.{ TC "Figure 2.11 Slab heat loss for office building in five locations." \l 5 }
All comply with ASHRAE Standard 90.1

The heat loss through the slabs found using this model are greater than what one would find using methods from the ASHRAE Handbook of Fundamentals (ASHRAE, 1993). The handbook recommends a method developed by Wang (1979) and Bligh et al (1978) that relates the heat loss through a slab to the length of the perimeter. The method relies on equation 2.3 below:

$$\dot{q}_{slab} = F_2 P (t_i - t_o) \quad (2.4)$$

The coefficient F_2 is the heat loss per foot of building perimeter and has different values depending on construction types and climates. For a construction similar to that of the retail building, and for the climate in Madison, WI, F_2 has a value of 0.56 Btu/h- F. Using this value in equation 2.3 yields a heat loss of 29,000 Btu/h (8500 W) for inside temperature of 70 F and an outside temperature of 0 F. On a unit area basis this yields an overall heat loss of 2.5 W/m^2. This is lower than the value estimated by the finite element model which ranges from 3 to 4 W/m^2 over the course of the year.

There are several reasons why the results of the finite element model are higher than that predicted using the ASHRAE method. First, the ASHRAE method was intended for residential applications. There may have been some underlying assumptions about the construction around the perimeter that are not applicable for commercial building construction. Second, the depth of the perimeter insulation around the footing in the ASHRAE method is unspecified. They may have assumed insulation to a greater depth than was used in the finite element model. Lastly, the level of insulation listed in the ASHRAE tables was slightly higher than that used in FEHT model. The perimeter heat loss in ASHRAE Fundamentals is only given for two cases - no insulation and insulation to R = 5.4 F-ft2-h/Btu. The FEHT model was run for cases where R = 5.0 F-ft2-h/Btu. This slight difference in R values could be responsible for some of the difference in the predicted heat loss.

The FEHT model did, however, show good agreement with other slab-loss models. BASECALC™ is a computer program designed by CANMET, Natural Resources Canada, to model heat losses from basements and slabs-on-grade (Beausoleil-Morrison et al, 1995). BASECALC™ is based on a two-dimensional finite element method developed by Mitalas, modified to include three dimensional effects and to account for heat loss through conduction to adjacent exterior walls. A simulation was run on BASECALC™ using the same boundary conditions as the FEHT model. For Madison, the annual heat loss through the slab found by BASECALC™ agreed with the finite element model to within 4%. Although the results of the FEHT model could not be verified with experimental data, this close agreement with other validated models is a good indication that the model is accurately predicting heat loss through the building slab.

2.3 Conclusion{ TC "2.3 Conclusion" \l 2 }

A two-dimensional finite element computer model was developed to calculate the heat loss through building slabs on an hourly basis. The results of the method agree well with other validated slab heat loss models using similar input weather data and building characteristics. This model, therefore, will provide a basis for developing estimates of heat loss through building slab-on-grade foundations, and analyzing the effect of adding perimeter insulation on building heating and cooling loads .

The FEHT slab model did, however, predict slab heat losses that differed significantly from simplified methods recommended in the ASHRAE Handbook of Fundamentals. The handbook gives heat loss estimates for only a limited number of slab configurations and insulation levels. As commercial buildings envelopes become more efficient and well insulated, the heat loss through building slabs becomes a more important issue. It may be time to update the methods used for quick calculations of slab and below grade heat losses. A wider array of correlations for different weather conditions, slab configurations, and insulation levels seems warranted.