Build Simul (2008) 1: 311–325
DOI 10.1007/s12273-008-8325-3

RESEARCH ARTICLE

Evaluation of Ventilation Code Requirements for Building Crawl Spaces

Brian D. Erickson, Zhiqiang (John) Zhai(✉)

Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, CO 80309-0428, USA

Received: 1 August 2008 / Revised: 13 September 2008 / Accepted: 15 September 2008

Abstract Building ventilation code requirements for crawl spaces were reviewed from 1937 to today and though remain largely unchanged, provide designers and builders flexibility in moisture control methods. This study evaluates the current building ventilation code requirements for at-grade and below grade crawl space using computational fluid dynamic (CFD) software with experiment inputs. The research first tested the soil moisture evaporation rate from two monitored crawl spaces in Colorado, US, which produces an average moisture load of 13.75 grains/(ft^2·h) (9.6g/(m^2·h)) and a maximum load of 42.7 grains/(ft^2·h) (29.8g/(m^2·h)). The soil moisture evaporation rates identified align well in magnitude with those recorded in the literature, supporting the estimation method used. The experiment reveals that plastic ground cover can effectively reduce the moisture load from the soil by an average of 93%. The study then developed a CFD model of the monitored crawl space to assess the necessity and effectiveness of various ventilation code requirements. The space effective leakage area to the exterior was determined through field pressurization testing and CFD analysis to be approximately 0.26in.^{2}/ft^2 of floor area. The CFD predictions, validated with the measured data, verify that the building code requirements for at-grade crawl spaces appear sufficient, but have limitations for below grade crawl spaces. Sealed crawl spaces perform better in humid climates, supporting previous research, and mechanical ventilation is justified for below grade crawl spaces only. The paper provides suggestions for the revisions to the current building code to recognize below grade underfloor spaces.

Keywords crawl space, ventilation, computational fluid dynamics (CFD), soil moisture evaporation, building code

1 Introduction

Crawl spaces have been the focus on research and debate in North America starting in the 1930s and continuing strongly today. However, despite the research, case studies, and experience of academics and building researches, there does not appear to be a consensus as to the proper method of crawl space ventilation and moisture control, especially for the varied climate regions throughout North America. Some have shown that ventilation of a crawl space is unnecessary so long as a ground cover (vapor retarder) is applied to the soil, and that introducing outdoor air into a cool crawl space in the summer can actually raise relative humidities to the point of wood decay (Lstiburek 2004; Karagiozis 2005; Davis et al. 2005). On the other hand, the primary moisture load in dry or cold climates does not necessarily come from the outdoor air, but rather the soil at the crawl space floor. Thus, dilution with drier outdoor air can be advantageous in preventing mold and biological decay from occurring.

The building codes began including prescriptive requirements for underfloor ventilation (crawl spaces) as early as 1937 based on the literature reviewed by the authors. The building codes are not fluid in adapting to the most current research and experience of building researchers, but do allow flexibility. The limitations with prescriptive building code requirements increase when the crawl space

E-mail: John.Zhai@colorado.edu

occurs below grade, which is a fairly common basement foundation construction practice in the Middle West of US such as Colorado. Below grade underfloor spaces do not have a natural air exchange with the exterior dry air and therefore are generally more prone to moisture control problems.

There is an on-going effort to develop and verify various computer simulation models that can be used to predict the performance of crawl space construction and ventilation methods in multiple climate zones. One advanced simulation tool is ORNL's MOISTURE-EXPERT v. 2.0, which has been validated to predict the movement of water vapor and temperature within crawl spaces (Karagiozis 2005). To accurately model the performance of crawl space ventilation and moisture control methods, the program must have the ability to calculate heat, air, and moisture transport equations. This requirement lends itself well to computational fluid dynamics (CFD) that solves the Navier-Stokes transport equations. While the CFD model does have its limitations, most significantly of the inherent moisture storage characteristics of materials and their effect on heat transfer, it can provide a reasonable estimation as to the effectiveness of various building ventilation code requirements for crawl space. In order to prepare a model, one must provide a reasonable estimation for the primary moisture load source in dry climates: the soil.

This paper quantitatively evaluates and compares the effectiveness of current crawl space moisture control requirements by using CFD simulation and analysis. The CFD model was established with inputs from field testing, and calibrated against the measurement results. The study supports the simplified method of estimating the moisture load from soil and verifies that a commercially available CFD simulation tool can accurately predict the moisture load profile within a crawl space. Based on a series of CFD parametric studies, the research provides comments and recommendations for current prescriptive building code requirements for ventilation and moisture control of at-grade and below grade crawl spaces.

2 Estimation of soil evaporation

2.1 Previous research

The estimation of soil evaporation in crawl spaces chosen by Trethowen (1994) was that of "free-water lysimetry." As stated by Trethowen, "*a lysimeter is essentially a bucket*" that is filled with soil and periodically weighed. Free-water lysimetry assumes the evaporation rate of saturated soil is equal to that of free water, demonstrated by previous work referenced by Trethowen. The soil evaporation method used by Trethowen produced an average soil evaporation rate of 23.7 grains/(ft^2·h) (16.5g/(m^2·h)) and a maximum rate of 41.8 grains/(ft^2·h) (29.2g/(m^2·h)). This was similar to the average soil evaporation rate estimated by Britton in the 1949 study of 29.3 grains/(ft^2·h) (20.4 g/(m^2·h)) (Rose 1994). Not surprisingly, Britton utilized a similar method of estimation.

In 1998, Kurnitski performed research on estimations of soil evaporation rates using a different method, noting limitations of free-water lysimetry (Kurnitski 2001). Kurnitski's estimation involved placing a series of data loggers throughout two identical crawl spaces, one with natural ventilation and one with mechanical ventilation. Kurnitski measured air change rates, temperature, and humidity concentrations on both crawl spaces for nearly two years. If one ignores the moisture storage capacity of the materials and assumes no free water is available inside the crawl space (Kurnitski 2001), then the measurements by Kurnitski can be used in the steady state moisture transfer equation:

$$w_{\text{out}} \cdot q_{\text{v}} + g = w_{\text{air}} \cdot q_{\text{v}} \tag{1}$$

where w_{out} is the humidity volume of outdoor air in grains/ft^3 (g/m^3), q_{v} is the air change rate in the crawl space in ft^3/min (m^3/s), g is the soil evaporation rate in grains/min (g/s), and w_{air} is the humidity volume of the extract (crawl space) air in grains/ft^3 (g/m^3).

Kurnitski introduced an alternate method for estimation of soil evaporation at the boundary layer by the following mass transfer equation:

$$g = \beta \cdot (w_{\text{ground}} - w_{\text{air}}) \cdot A \tag{2}$$

where β represents the mass transfer coefficient in ft/h (m/s), w_{ground} is the humidity volume at the soil boundary in grains/ft^3 (g/m^3), and A is the area of the crawl space (soil) floor in ft^2 (m^2) (Fig. 1).

Of interest is the mass transfer coefficient, β, which if known can provide an estimation of the soil evaporation rate in grains/min (g/s).

As derived by Kurnitski (2001), the mass transfer coefficient, β, can be calculated based on the following

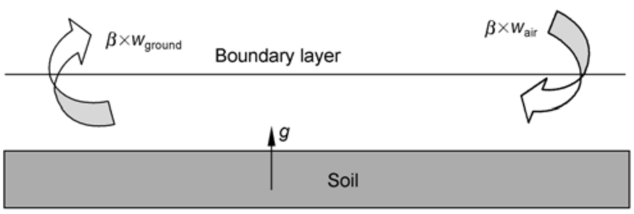

Fig. 1 Mass balance at boundary layer

equation:

$$\beta = \frac{\alpha}{\rho \cdot c_p} \tag{3}$$

where α is the convective heat transfer coefficient in Btu/(h·ft^2·℉) (W/(m^2·K)), ρ is the density of air in lb/ft^3 (kg/m^3), and c_p is the specific heat of air in Btu/(lb·℉) (J/(kg·K)).

Kurnitski (2001) also estimated the convective heat transfer coefficient, α, by Eq. (4) or (5):

$$\alpha = 0.3876 \cdot \left(\frac{T_{\text{bottom}} - T_{\text{top}}}{1.8} \right)^{1/3} \tag{4}$$

(T in ℉, α in Btu/(h·ft^2·℉))

or

$$\alpha = 2.2 \cdot \left(T_{\text{bottom}} - T_{\text{top}} \right)^{1/3} \tag{5}$$

(T in K, α in W/(m^2·K))

where T_{bottom} is the temperature at the soil boundary and T_{top} is the temperature at the top of the crawl space. Kurnitski provided the relationship to include forced convection at the boundary layer in calculating the convective heat transfer coefficient below in Eq. (6) (in SI unit):

$$\alpha = 2.2 \cdot \left(T_{\text{bottom}} - T_{\text{top}} \right)^{1/3} + 4 \cdot v \tag{6}$$

where v is the velocity in m/s of the airflow across the soil surface, either by mechanical means or natural airflow.

The testing and methodology used by Kurnitski to estimate soil evaporation resulted in considerably lower evaporation values when compared to Trethowen, which is expected as free-water lysimetry assumes saturated conditions. The advantage to using the techniques by Kurnitski for soil evaporation estimation are as follows:

- commercially available data logging software is easily obtained compared to lysimetry equipment;
- the cost of data measurements is less;
- data measurements from loggers do not require frequent inspection;
- the results can be used for "in-situ" evaporation rather than fully saturated soil conditions.

Therefore, in order to estimate values for the soil evaporation rate inside two crawl spaces for use in the CFD model, the methodology provided by Kurnitski (2001) was implemented. Implementing this technique will also provide the benefit of validating the results obtained earlier by Kurnitski and criticizing the methodology.

2.2 Field measurement descriptions

Two at-grade crawl spaces in two typical high-end detached single family houses, within the same subdivision of Colorado, were monitored for a period of approximately one month to:

(1) estimate the rate of moisture evaporation from the soil;
(2) evaluate the effectiveness of a ground cover over the soil in reducing evaporation;
(3) estimate the natural air changes without ventilation (determine the effective leakage area);
(4) validate the methodology provided by Kurnitski.

It is noted that hourly data readings for a period of only one month may not provide sufficient accuracy for validation, but due to time constraints, only one month was available for testing (the crawl spaces in question were to be repaired on a set schedule). It is also noted that only two crawl spaces may not be sufficient to provide statistically adequate results. These limitations, while present, do not have a significant impact on the general purpose of this study.

The two crawl spaces of the two homes were almost same in size (13ft by 21ft and 4ft deep) and identical in location within the house and orientation (both faced northwest). The crawl spaces were located immediately below a small portion of the first floor with two exterior walls exposed to the ambient and two comment walls between crawl space and the basement. Crawl space A did not have a ground cover while crawl space B did have a ground cover (Fig. 2). With the aim to find moisture evaporation rate from soil, both openings connecting the crawl spaces to the ambient and to the basements were sealed off during the monitoring period to minimize the air

Fig. 2 Interior of crawl space A (no ground cover)

exchanges to the basement and to the outdoors (this however was proven to have little success).

Data loggers were placed at the same locations throughout both crawl spaces and the homes in question. The data loggers, manufactured by Dickson, were programmed to record temperature (℉) and relative humidity (%) at hourly intervals. Loggers were also placed outdoors and within the homes to monitor other areas of interest. A general description of the data logger locations is described below:

- bottom center of crawl space, approximately 1.5in. above the soil;
- top center of the crawl space, approximately 3ft above the soil;
- top exterior corner of crawl space, near outdoor wall;
- top interior corner of crawl space, near basement wall;
- basement ceiling, about 5ft outside crawl space;
- two (2) loggers were placed outdoors:
  – below walkway ramp, protected from sun and elements
  – at stone chimney inside covered patio
  The data from the two loggers were averaged to provide typical outdoor conditions.

2.3 Field measurement results

Overall, the data showed the humidity concentrations in crawl space A were higher than crawl space B, which is reasonably attributed to the presence of the vapor retarder as shown in Fig. 3. Within the crawl space A, the humidity concentrations were notably higher near the soil as compared to the top of the crawl space, which verifies that evaporation is occurring from the soil and the method of moisture load estimation by Kurnitski may be useful.

2.4 Soil evaporation estimation

Equations (2) – (4) were utilized to estimate the water vapor load originating from the soil in crawl space A and the results shown in Fig. 4.

As shown in Fig. 4, the soil evaporation in crawl space A was greatest during the first two days of measurement before apparently reaching "steady state" evaporation. Note the similar trend in humidity concentration shown in Fig. 3, where the humidity concentration at the crawl space bottom increased during the first two days of data logging. This is

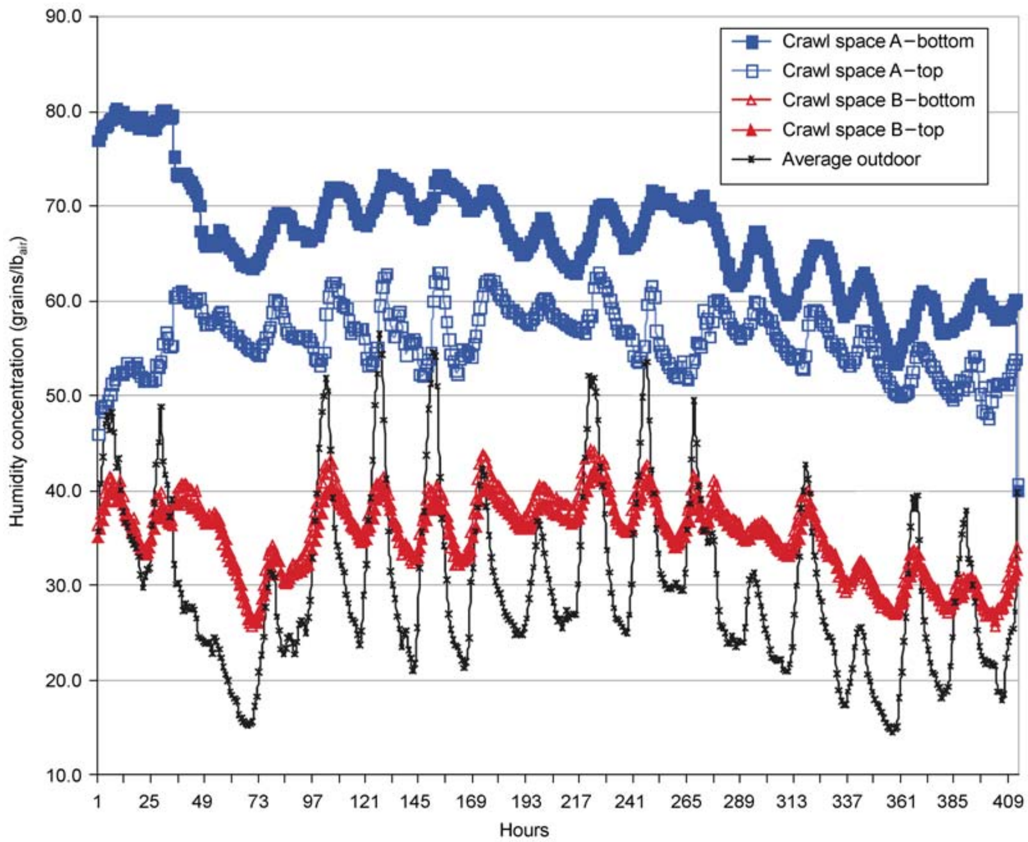

Fig. 3 Data logging results of humidity ratio for crawl spaces A and B

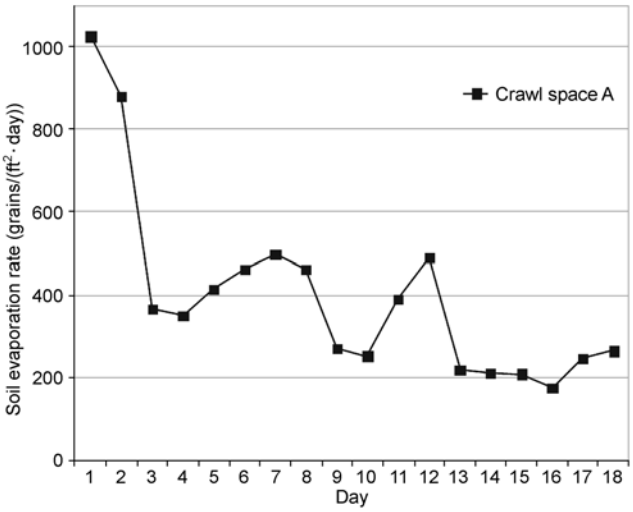

Fig. 4 Daily soil evaporation rate for crawl space A

due to the fact that crawl space A initially contained a vapor retarder that was removed immediately prior to the data logger placement. The vapor retarder was causing a "build up" of water vapor at the soil surface and once removed, that water vapor was allowed to evaporate until conditions reached steady state. Thus, the initial two day evaporation rate should be near that of saturated soil, whose values were estimated by Trethowen. Indeed, a comparison of the initial evaporation rate compared to Trethowen, shown in Table 1, illustrates the potential moisture load from soil within crawl spaces if precautions are not met to prevent the soil from becoming saturated. These precautions include site grading away from foundation walls, proper placement of downspouts to control roof runoff, dampproofing the outside of the foundation wall, placement of perimeter drains, all of which are not controversial within the building research industry but too often are ignored or forgotten in practice.

The estimation of soil evaporation rate in crawl space A was similar but higher when compared to the results obtained by Kurnitski. Specifically, the average soil evaporation rate at steady state (after day 2) was 13.75 grains/(ft^2·h),

Table 1 Comparison of soil evaporation results

	Soil evaporation rate (grains/(ft^2·h))	Mass transfer coefficient β (ft/min)
Measured average	13.75	23.5
Measured max	42.7	—
Kurnitski—low	5.2	14.17
Kurnitski—high	8.2	21.25
Trethowen—average	23.7	—
Trethowen—max	41.8	—
Britton—average	29.3	—

compared to the range provided by Kurnistki of 5.2 to 8.2 grains/(ft^2·h), within 60%. Also, the mass transfer coefficient β estimated here was 23.5ft/min, compared to the range given by Kurnitski of 14.2 to 21.3, or within 10%.

It should be noted that Kurnitski did state that Eq. (2) tends to overestimate the soil evaporation rate, which appears to be the case with the measured data. Nonetheless, the results were within an order of magnitude compared to the previous research reviewed. Therefore, the methodology put forth by Kurnitski for estimation of soil evaporation is supported with the understanding that the results may overestimate the moisture load.

Some differences in the soil evaporation rates between Kurnitski and this measurement can be attributed to differences in soil types, groundwater conditions, ambient conditions, and ventilation rates. Also, the limited number of data points collected during this study likely influences the results. As shown in Fig. 4, the trend is the soil evaporation rate decreases as time continues. If this study would have been carried out for over one year, such as Kurnitski's, then the average evaporation rate would likely be less than the 13.25 grains/(ft^2·h) reported.

The vapor retarder reduced the evaporation rate between 77% and 100%, for an average effectiveness of 92.6%. These results were similar to what is generally accepted in the industry, that a vapor retarder can reduce the soil moisture load from between 75% and 95%.

It is not debatable that the placement of a vapor retarder over the soil is an effective means to control humidity in crawl spaces. However, the practice is still not mandated by building codes. What is debatable is whether the presence of a vapor retarder alone, without any means of ventilation, is sufficient to prevent condensation and decay within crawl spaces. This issue will be explored in greater detail later in this paper.

3 Measurement of air infiltration

To understand the moisture in and out of the at-grade crawl spaces via infiltration requires the measurement of the effective air leakage area (ELA) of these spaces. In general accordance with ASTM E779-99, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, and the methodology described by Krarti (2000), a pressurization fan was set up in the crawl space access door (Fig. 5) and the differential of pressure was measured between the crawl space and the basement at intervals of 5Pa, with the basement pressure assumed to be that of the outdoor pressure (two windows in the basement were open to the exterior). The results were used to calculate the ELA based on the reference pressure of 4Pa.

Fig. 5 Pressurization test in crawl space

This reference pressure was determined to be reasonable based on subsequent measurement of the pressure differential between the crawl space and exterior.

The test results were plotted in a log-linearized regression technique to determine coefficients C and n from the following equation:

$$\dot{V}_{\mathrm{ref}} = C \cdot \Delta P_{\mathrm{ref}}^{n} \tag{7}$$

where ΔP_{ref} is the reference pressure differential, here 4Pa and $\dot{V}_{\mathrm{ref}}$ is the reference air infiltration rate in ft^3/min. Once the coefficients were determined from Eq. (7), they were used in Eq. (8) to calculate the total ELA ($\mathrm{in.}^2$)

$$\mathrm{ELA} = 0.186 \cdot \dot{V}_{\mathrm{ref}} \sqrt{\frac{\rho}{2 \cdot \Delta P_{\mathrm{ref}}}} \tag{8}$$

Here ΔP_{ref} is the reference pressure (0.016in.WG) and $\dot{V}_{\mathrm{ref}}$ was found in Eq. (7). The results showed an abnormally large total ELA of about 1,200in.^{2} for a relatively small area, or 4.4in.^{2}/ft^2 of floor area (compared to 0.93in.^{2}/ft^2 found by Trethowen). It was observed that the leakage through the common walls between the basement and crawl space was very significant and must be taken into account in the CFD model.

4 Calibration and validation of CFD model

The CFD technique has become a powerful tool for indoor environment analysis since the 1970s due to developments in computer programming and turbulence models (Zhai 2006). The environmental conditions within a crawl space require an analysis of airflow, temperature, and water vapor displacement, which can be solved by CFD techniques and specifically a computer software program. The choice to use CFD as a tool for crawl space analysis must be based on realistic expectations of its performance, cost, and effort required. For example, it would not be realistic to use CFD to analyze a crawl space moisture control technique if the time involved takes days or even weeks at a significant cost that exceeds the cost of the crawl space moisture control technique.

This study focuses on using a calibrated CFD model to evaluate the current prescriptive regulations for crawl space moisture control. The field test was to help establish a simulation model with reasonable key boundary conditions (i.e., soil evaporation rate and air infiltration rate). An integrated calibration and validation process has been employed to calibrate the missing crucial information (i.e., accurate boundary conditions for CFD), and to ensure that the model can in overall represent the real space and conditions and thus be used for parametric studies. In such a calibration and validation procedure, a portion of experimental results were used to fine-tune the model so that an agreement between predicted and measured results can be reached. The calibrated model provides more prediction results, which can then be compared and verified against the other portion of experimental results (which have not been used during the calibration).

4.1 Base case setup

The base CFD model established was for crawl space A, described earlier within this paper. Crawl space A was approximately 273ft^2 with 4ft depth below a first floor kitchen and dining room. The crawl space had two perimeter walls exposed to the exterior, each with one vent opening that was closed off during the data logging period. The crawl space also had two walls exposed to the basement, with the long wall containing many openings that were attempted to be sealed.

4.1.1 Basic flow characteristics

The airflow inside crawl space A is affected by heat transfer from the perimeter and common walls, upper floor, soil, and the infiltration of the outdoor air. The humidity concentration within the crawl space is affected by the soil source flux (grains/h), outdoor and basement air humidity concentrations, temperature profiles, and the air movement. The parameters to be solved are

– air pressure (Pa),
– airflow velocity (m/s) in U, V, W,
– air temperature (℃),
– turbulence variables (k, ε),
– humidity ratio (HR) (g/kg),
– relative humidity (RH) (%).

The airflow has been considered as incompressible but with buoyancy effect included. The classical Boussinesq approximation has been used due to relatively small density changes under typical room conditions. Since all surface temperatures were given from experiments, the radiation model was not needed for the simulation.

4.1.2 Boundary conditions and calibrations

Table 2 summarizes the primary boundary conditions specified in the base case. The surface temperature conditions were measured within the crawl space. The two perimeter walls of the crawl space were input by using the average temperatures of 62.6℉ (17℃), while the common walls were a constant temperature of 64.4℉ (18℃). For the CFD model, average temperatures of 62℉ (16.7℃) and 65℉ (18.3℃) were used for the soil and the upper floor, respectively. Note that these values were varying more or less throughout the month of data collection but for the purpose of a steady-state CFD evaluation, they were assumed to remain constant. The relatively constant indoor and basement temperatures justify the boundary conditions for the floor and common walls. The outdoor air temperature, however, fluctuated between 37℉ (3℃) and 61℉ (16℃) during the test days and likely influenced the temperature of two perimeter walls. The thermal mass of the soil and the foundation (approximately 2/3 of the foundation wall is below grade) will damper this fluctuation. The constant temperatures of other surfaces will also damper the temperature fluctuations of the perimeter walls via radiation. Although it would be ideal if an unsteady CFD simulation could be performed with dynamic surface temperatures, it is unrealistic for a parametric study with a focus on general regulation assessment. The numerical experiments

Table 2 Summary of boundary conditions in base CFD

Geometries	13ft(4m) × 21ft(6.4m) × 4ft(1.2m)
Outdoor conditions	T_{air} = 50.5℉ (10.3℃), HR = 3.3g_{vapor}/kg_{air}, P_{air} = 0Pa
Indoor conditions (include basement)	T_{air} = 64.4℉ (18℃), HR = 5.4g_{vapor}/kg_{air}, P_{air} = 0Pa
Perimeter walls (to outdoor)	$T_{surface}$ = 62.6℉ (17℃)
Common walls (to basement)	$T_{surface}$ = 64.4℉ (18℃)
Ground (soil surface)	$T_{surface}$ = 62℉ (16.7℃), HR = 10.2g_{vapor}/kg_{air}
Ceiling (upper floor)	$T_{surface}$ = 65℉ (18.3℃)
ELA to outdoor (6%)	A = 70in.^{2} (0.045m^2), P_{air} = 1Pa
ELA to basement (77%)	A = 893in.^{2} (0.576m^2), P_{air} = 0Pa
ELA to upper floor (17%)	A = 198in.^{2} (0.128m^2), P_{air} = 0Pa

further confirm such steady-state assumptions can provide a reasonable estimation of the crawl space humidity concentrations (Fig. 10).

Modeling infiltration in CFD is always a challenge due to the uncertain location and size distributions. The total ELA obtained from the measurements had to be separated by the perimeter walls, common walls, and upper floor. Initially, an assumption, on the basis of the field observations and tests, was made that 70% of the total ELA occurred at the basement walls, 20% at the floor, and 10% occurred at the perimeter walls. These ratios were varied in CFD until the predicted humidity ratios were near the measured humidity ratios at the same locations for one specific time period (hour) of test. This calibration process resulted in an ELA distribution of 77% along the basement walls, 17% at the floor, and 6% along the exterior walls. The placements of leakage on the floor and walls in CFD were specified based on the field observations and local smoke tests. As shown in Fig. 6, the ELA at the exterior wall was placed at sill plate height, directly below the joists. The ELA at the basement wall was distributed along the base plate and the upper joist penetrations with a ratio of 22% and 78%, respectively.

The calibrated ELA for the exterior wall (6% of total) equates to an outdoor ELA of approximately 70in.^{2} (2 of four walls) or 0.26in.^{2}/ft^2 of floor area. This ELA value can be further examined by a back-of-the-envelope calculation using the LBL infiltration model developed by Sherman and Grimsrud (1980). The LBL model, although not developed for crawl spaces, can roughly determine the average infiltration rate under normal climatic conditions by Eq. (9) below. Assuming applicable to the crawl space of interest, Eq. (9) gives the average infiltration rate of 45.5ft^3/min (cfm) for the test period.

$$\dot{V} = \mathrm{ELA} \cdot \left(f_s \cdot \Delta T + f_w \cdot v_w^{\ 2} \right)^{1/2} \tag{9}$$

where ΔT is the temperature difference between the crawl space and the outdoor, f_s is the stack coefficient (=0.005, reduced for crawl space height), v_w is the outdoor wind speed (obtained from NOAA daily averages for the monitoring period), and f_w is the wind coefficient (=0.0065, reduced to compensate for the proximity to grade).

To validate the air exchange rate calculated via Eq. (9) with the calibrated exterior ELA, the computed hourly soil evaporation rate was inserted in Eq. (1), yielding an average air exchange rate of 36.1cfm. This is approximately 25% lower than the calibrated air exchange rate. Differences between the two values are likely attributed to the fact that the daily average wind speed was used in Eq. (9) for every hour, a condition that does not occur in practice and thus tends to overestimate the average infiltration rate. Also, the

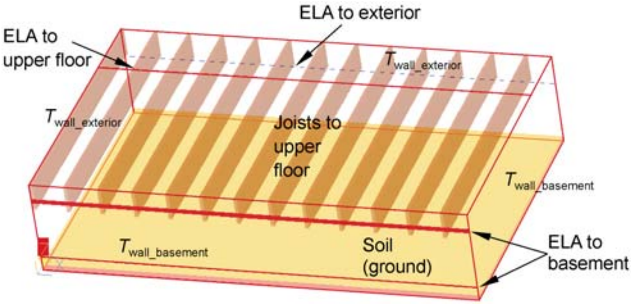

Fig. 6 CFD case setup for crawl space A including floor joists, walls, soil, and ELA distributions

wind and stack coefficients may not be directly applicable to crawl spaces. Nonetheless, the values were within an order of magnitude and support the calibrated ELA distribution in the CFD model.

The outdoor and basement air conditions were obtained directly from hourly measurements and input to predict the crawl space humidity concentrations against measured data at specific hours of interest. Four data sets, representing four typical time hours, were chosen to validate the calibrated CFD model.

4.2 Validation of CFD predictions

4.2.1 Influence of turbulence models

Selecting an appropriate turbulence model is important for Reynolds-Averaged Navier-Stokes (RANS) CFD modeling to obtain an accurate prediction. It is known that Reynolds stress turbulence models require additional computing time due to the six additional equations that need to be solved without a significant increase in accuracy. Therefore, only eddy viscosity turbulence models were considered in this research. In order to determine the impact of the selection of turbulence model, a turbulence model study was conducted using standard two-equation k-ε model (KEMODL), the KECHEN model, the KERNG model, and the LVEL model. Conventional wall function (log-law) has been used for all the turbulence models tested. The KECHEN model was selected for all the later simulations as it appears to provide "average" values compared to the other two-equation turbulence models (Fig. 7).

4.2.2 Influence of grid number

All of the objects in the crawl space studies were rectangular and therefore body-fitted, unstructured grid models are not necessary. A Cartesian grid system with structured mesh was chosen for computational speed and ease in obtaining location-specific results. A systematical refinement for the grid resolution was conducted, with resolutions ranging from 24,000 cells up to 537,000 cells. The comparisons of humidity ratio are shown in Fig. 8.

It is generally accepted that the higher resolution can provide more accurate results, but at the expense of significantly added computing time. Clearly, the low grid resolution does not provide accurate results, especially when compared to the measured values. However, the two "medium" grid values provided results near the measured value as shown in Fig. 8. While the fine grid did provide greater accuracy near the exterior corner, the difference between the medium grids is not sufficient to justify the increased computing time. Indeed, the computing time associated with the very fine grid (537,000) was approximately 8 hours, compared to the medium grids (105,000 to 225,000) between 1 and 2 hours, on a modern laptop computer. Since this study was mainly interested in assessing the prescriptive regulations for crawl space moisture controls via a number of parametric studies, grids between 110,000 and 150,000 were chosen, in which the $y+$ values were beyond the laminar sub-layer and in the log-law region. Figure 9 illustrates the typical grids used.

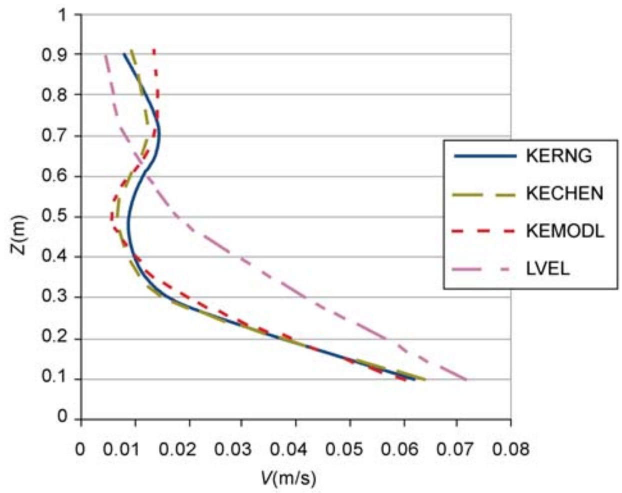

Fig. 7 Turbulence model comparison (velocity profile at X=1m, Y=3m)

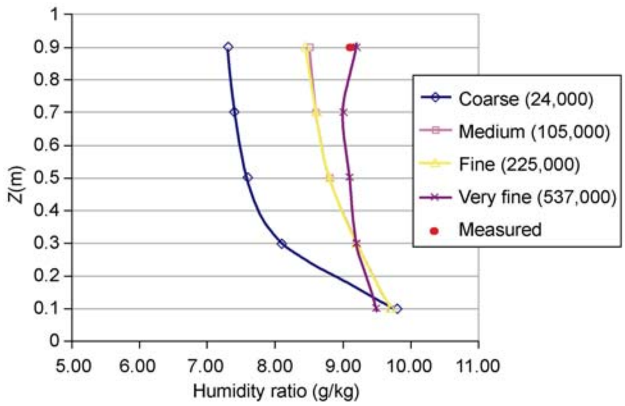

Fig. 8 Grid independence study (humidity ratio profile at X=1m, Y=0.5m)

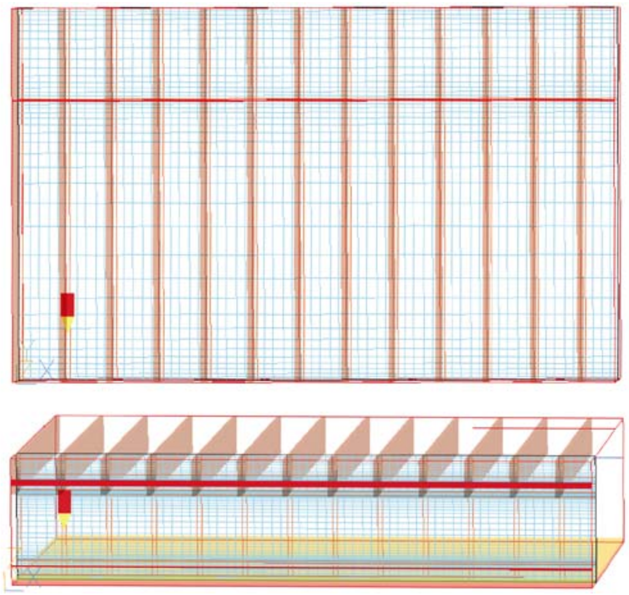

Fig. 9 Typical grids in *XY* (above) and *XZ* (below) planes

4.3 Comparison of simulation with experiment

Figure 10 illustrates the comparison of the CFD predictions with the measured data at the corner data logger (X=1m, Y=0.5m, Z=0.9m) at four hours of interest. Similar results were obtained for the center and opposing corner data logger, verifying the accuracy of the CFD model.

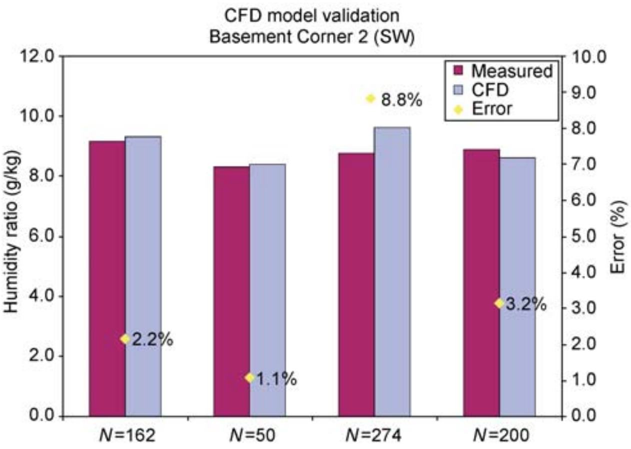

Fig. 10 CFD model verification against experiment measurements where N is N^{th} test hour

The humidity concentration contour in Fig. 11 shows a lower concentration near the exterior wall and a higher concentration near the basement wall. This correlates to the measured data, where the data logger nearest the exterior wall consistently recorded lower humidity concentrations compared to the logger nearest the basement wall. Based on these results, it is concluded that CFD software can be used as an analysis tool to predict crawl space environmental

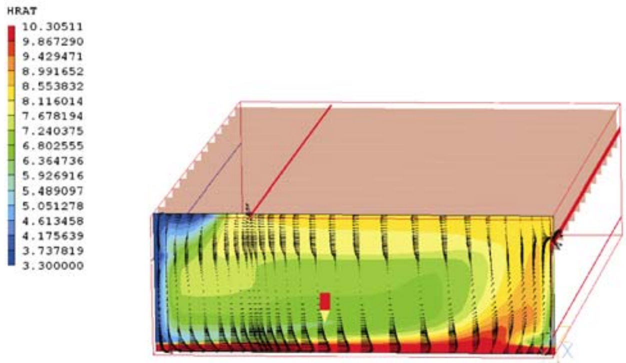

Fig. 11 Humidity concentration contour on a *YZ* plane where HRAT (humidity ratio) is measured in g_{vapor}/kg_{air}

conditions within a reasonable degree of certainty if some measurement data can be used to develop and calibrate the model.

5 Crawl space ventilation and moisture control requirements—CFD analysis

5.1 At-grade crawl space

5.1.1 Code requirements

Reprinted below are the requirements of the 2003 International Residential Code (IRC) (International Code Council 2003)—which are unchanged in the 2006 IRC:

Section 408—Underfloor Ventilation

- *R408.1. The under-floor space between the bottom of the floor joists and earth under any building (except space occupied by a basement or cellar) shall be provided with ventilation openings through the foundation walls or exterior walls. The minimum net area of ventilation openings shall not be less than 1 square foot for each 150 square feet of under-floor space area. One such ventilation opening shall be within 3 feet of each corner of said building.*
- *R408.2. The minimum net area of ventilation openings shall be less than 1 square foot for each 150 square feet of under floor space area. Once such ventilation opening shall be within 3 feet of each corner of the building. Ventilation openings shall be covered for their height and width with any of the following materials provided that the least dimension of the covering shall not exceed 1/4 inch.*
  1. *Perforated sheet metal plates not less than 0.070 inch thick.*
  2. *Expanded sheet metal plates not less than 0.047 inch thick.*
  3. *Cast iron grilles or grating.*

4. *Extruded load-bearing brick vents.*
5. *Hardware cloth of 0.035 inch wire or heavier.*
6. *Corrosion-resistant wire mesh, with the least dimension being 1/8 inch.*

- *Exceptions:*

1. *Where warranted by climatic conditions, ventilation openings to the outdoors are not required if ventilation openings to the interior are provided.*
2. *The total area of ventilation openings may be reduced to 1/1500 of the under floor area where the ground surface is treated with an approved vapor retarder material and the required openings are placed so as to provide cross-ventilation of the space. The installation of operable louvers shall not be prohibited.*
3. *Under-floor spaces used as supply plenums for distribution of heated and cooled air shall comply with the requirements of Section M 1601.4.*
4. *Ventilation openings are not required where continuously operated mechanical ventilation is provided at a rate of 1.0 cfm for each 50 square feet of underfloor space floor area and ground surface is covered with an approved vapor retarder material.*
5. *Ventilation openings are not required when the ground surface is covered with an approved vapor retarder material, and the space is supplied with conditioned air and the perimeter walls are insulated in accordance with Section N 1102.1.7.*

The main prescriptive requirement involves ventilation openings to the exterior at each corner, with a total net-free area of $1ft^2/150ft^2$ of crawl space floor area. Note that a ground cover (vapor retarder) is not required if the 1/150 ratio is met, even though it has been shown that a vapor retarder can reduce the moisture load from the soil by 93%. If the designer and/or contractor does not elect to follow the 1/150 ventilation ratio, then four exceptions or differing methods are provided for in the building code, listed above (Exception #3 does not apply to an alternate ventilation method).

5.1.2 CFD analysis

These prescriptive methods of crawl space ventilation will be analyzed using the calibrated CFD model for the crawl space monitored and validated during this study. The actual soil evaporation rates will be implemented in the model, both with and without a vapor retarder, and typical mechanical ventilation methods will be simulated. The focus of this analysis is the dry regions such as Colorado, but a typical hot/humid climate such as Florida will also be simulated to determine the impact that outdoor conditions have on the building codes for ventilation and moisture control. A total of twelve (12) prescriptive building code cases were simulated using the validated CFD model, eight (8) in Colorado (Table 3), four (4) in Florida (Miami) (Table 4).

In Colorado, Fig. 12 indicates the current building code requirements are adequate in preventing critical relative humidities—below 80% as suggested by Viitanen and Salonvaara (2001)—during typical conditions. In fact, the results indicate that ventilation and/or passive openings are not necessary—natural air infiltration (with a relatively large ELA) and a ground cover is sufficient. This corresponds to the monitored results of both crawl spaces where, upon steady state, the humidities did not exceed 55% near the top of the crawl space as shown in Fig. 13.

In the humid climate (Miami), Fig. 14 indicates that ventilation or any openings to the exterior are less effective in reducing moisture in the crawl space than a sealed crawl space. Indeed, this conclusion correlates to the conclusion reached in a comprehensive study conducted in a humid climate (North Carolina) in a comparison between a sealed and ventilated crawl space (Karagiozis 2005; Davis et al. 2005).

Table 3 At-grade code analysis—case descriptions for Colorado

Case number	Code reference	Description	Ground cover	Soil evaporation rate (grains/(ft^2·day))
Case 1A	408.1	Passive openings only	No	330
Case 1B	408.1	Passive openings only	No	400
Case 1C	408.1	Passive openings only	No	500
Case 1D	408.1	Passive openings only	No	1000
Case 1E	408.1	W–E wind 8mph	No	500
Case 1F	408.1	N–S wind 8mph	No	500
Case 2	Exception 2	No ventilation	Yes	50
Case 3	Exception 4	Mechanical ventilation	Yes	50

Table 4 At-grade code analysis—case descriptions for Miami

Case number	Code reference	Description	Ground cover	Soil evaporation rate (grains/(ft^2·day))
Case 1M	408.1	Passive openings only	No	500
Case 2M	Exception 4	Mechanical ventilation	Yes	50
Case 3M	408.1	Passive openings, W–E wind	No	500
Case 4M	Exception 2	No ventilation	Yes	50

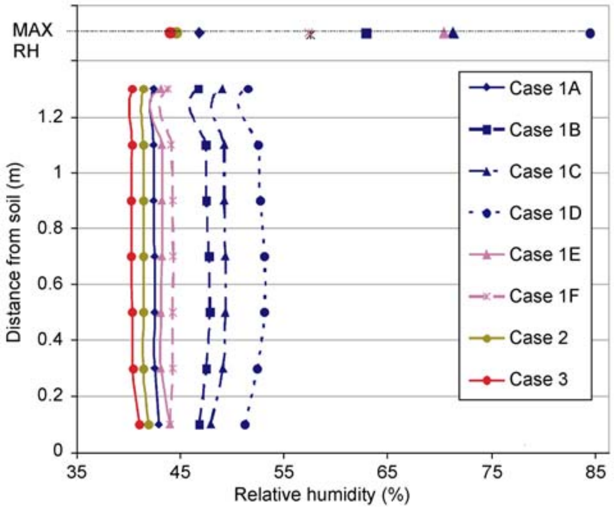

Fig. 12 At-grade code analysis results—layer averaged relative humidity for Colorado cases

5.2 Below grade underfloor space

5.2.1 Background and code requirements

One focus of this research is an analysis of the current prescriptive building code requirements on ventilation and moisture control for below grade underfloor spaces, also known as deep crawl spaces. A typical section of a deep crawl space is shown in Fig. 15.

Deep crawl space is one of the common basement foundation types at areas with unstable soils such as Colorado. They are implemented when basement floors cannot be properly supported by the site moisture-sensitive or otherwise unstable soils. In a typical basement design, the foundation walls are supported by grade beams and the basement slab "floats" on the soil. It is essential that the soils below the grade beams and basement floor slabs are properly compacted and treated to minimize future settling or upward heaving. When the soil at the building site contains the potential for expansion, an alternate method of basement foundation construction must be accomplished.

The typical method of ventilating a deep crawl space involves running a circular duct from the exterior into the crawl space, terminating above the soil typically 1 – 2ft. In the duct is an inline exhaust fan that moves air from the crawl space to the exterior. At another location within the crawl space, a similar duct is terminated into the crawl space from the exterior, but without a fan. This duct is used for "makeup" or the dilution air, while the inline fan duct is used to exhaust air. The fan is typically controlled by a humidity sensor.

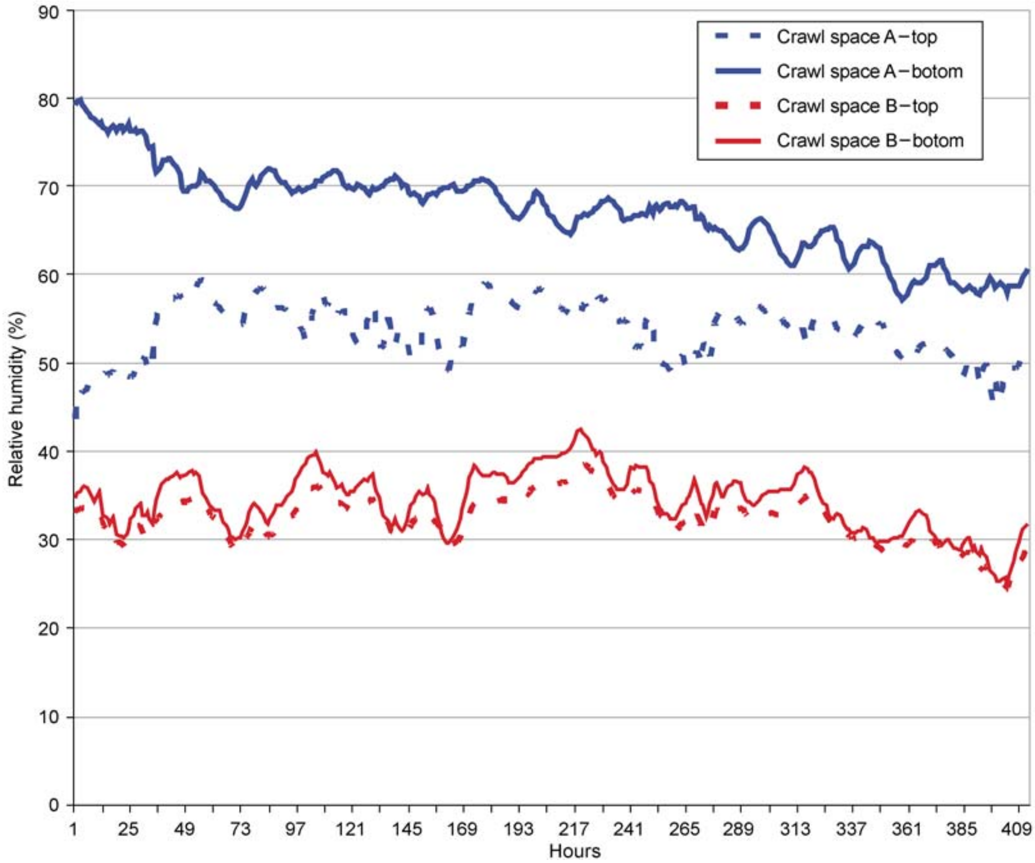

Fig. 13 Monitored results of relative humidity in crawl spaces A and B

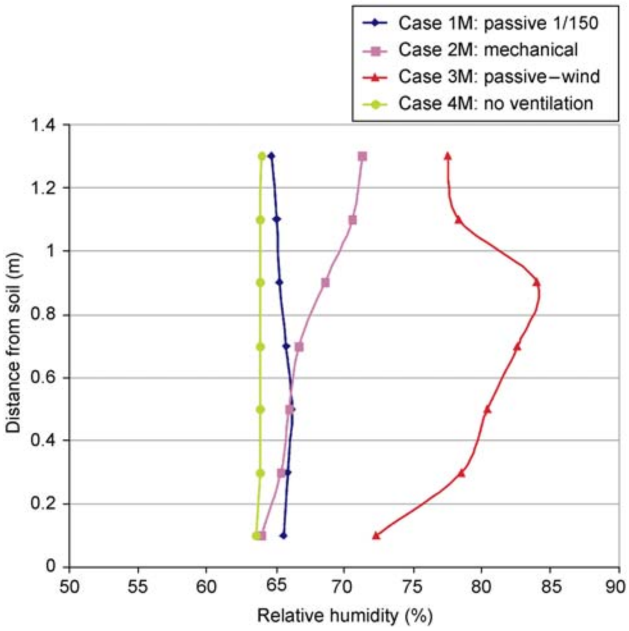

Fig. 14 At-grade code analysis results—layer averaged relative humidity for Miami cases

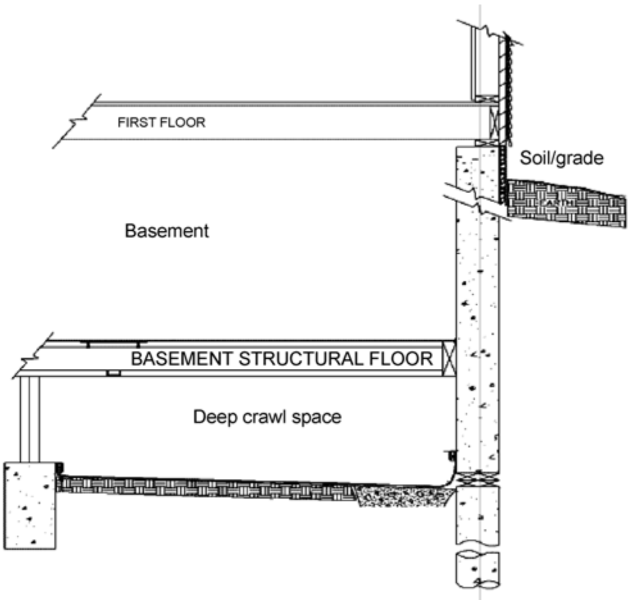

Fig. 15 Below grade underfloor space (deep crawl space)

In 2003, the state of Colorado formed a Moisture Management Task Force to determine guidelines for ventilation and moisture control of below grade underfloor spaces (MMTF 2003). The task force recognized the limitations with the current building code requirements and the humidity problems present in these spaces. The task force recommended the use of ground cover in all conditions and provided two general recommendations for ventilation. A general description of the two ventilation methods is below:

1. *Use of conditioned (indoor) air and transfer registers through the basement structural floor. An inline exhaust fan would be sized per ASHRAE 62.2 requirements of (7.5 ×Number of Bedroom +1) + (0.01 ×Floor Area in Square Feet). A centralized manifold system would provide mixing of air. Floor registers are placed every 250 square feet and sized per the table provided.*
2. *Use of a traditional one-intake and one-exhaust system. The fan capacity would be sized to provide a minimum of 2 and maximum of 4ACH. The intake duct will be insulated and placed as far as possible from the exhaust duct to promote mixing of air.*

It has been the experience of the task force that condensation can occur near the intake duct during winter conditions, hence the requirement for insulation. The "cold" duct from the exterior cools the surrounding air and even structural floor (in contact), which essentially raises the relative humidity of that air and lowers the temperature of the structural floor system to the point of condensation, or below the dew point temperature of the cooled air.

5.2.2 CFD analysis

A total 11 cases in four categories were simulated using the CFD software (Table 5). All cases involved a ground cover per building code Exception 4 requirements and the recommendations of the Colorado task force. The use of a ground cover is not debatable. What is of interest is the effectiveness of various ventilation methods, from traditional code requirements, to the task force recommendations, to no ventilation at all. The below grade underfloor space was 1200ft^2 and 3ft depth, typical in Colorado. Winter conditions were used for the intake boundary conditions of 50.5℉ (10.3℃), 34% RH. The floor was a constant temperature of 63℉ (17℃) and walls of 59℉ (15℃). Joists were not included for model simplification.

Case 1, typical cross ventilation with fan sizing per code requirements, appears to have its limitations if the soil evaporation rate approaches 50 grains/(ft^2·day), which is entirely probable in practice. Compared to Case 2, when fan sizing was based on ACH (or the cfm was imply increased) rather than the code 1cfm/50ft^2, the building code Exception 4 fan capacity sizing requirements does not appear to provide adequate dilution of crawl space air. Of particular interest is the value of 80% RH near the structural floor level, or Z=0.95m. It has been shown by numerous studies that decay and mold growth does not start on a cellulose surface until the relative humidity exceeds 80% for an extended period of time (Viitanen and Salonvaara 2001). The two cases where this could be a problem are Case 1 (code) and Case 4 (no ventilation). Indeed, the building code fan sizing requirements do not appear to provide significant improvements compared to no ventilation at all.

Table 5 Below grade underfloor code analysis—case descriptions for Colorado

Case number	Code reference	Description	Ground cover	Soil evaporation rate (grains/(ft^2·day))
Case 1A	Exception 2	Mechanical cross ventilation—code fan sizing (1cfm/50ft^2)	Yes	25
Case 1B	Exception 2	Mechanical cross ventilation—code fan sizing (1cfm/50ft^2)	Yes	50
Case 1C	Exception 2	Mechanical cross ventilation—code fan sizing (1cfm/50ft^2), with 90°elbow	Yes	50
Case 2A	MMTF	Mechanical cross ventilation—fan sizing 1ACH	Yes	50
Case 2B	MMTF	Mechanical cross ventilation—fan sizing 2ACH	Yes	50
Case 2C	MMTF	Mechanical cross ventilation—fan sizing 4ACH	Yes	50
Case 3A	MMTF	Centralized manifold floor transfer registers	Yes	25
Case 3B	Exception 4	Centralized manifold floor transfer registers	Yes	50
Case 3C	Exception 4	Centralized manifold floor transfer registers	Yes	100
Case 4A	Exception 2	No ventilation	Yes	25
Case 4B	Exception 2	No ventilation	Yes	50

Also, placing a 90° elbow at the base of the ducts increases the relative humidity near the soil and does not improve the dilution compared to the standard method of termination. This is because the dry air is directed above the soil in addition to the reduced velocity from the increased pressure drop.

However, Case 2 scenarios, with the capacity increased, rather than code Exception 4, does provide adequate dilution of the crawl space air, even with 1ACH. While sizing up to 4ACH does reduce the relative humidity, it does not appear to provide a significant improvement compared to 1 or 2ACH and the additional fan energy required is not justified. Thus, increasing the capacity to 2ACH is adequate for dilution. It is noted that the fan capacity is not necessarily directly related to the ACH, but for purposes of this study capacities sized for ACH were used.

Case 3, the centralized manifold requirements put fort by the Colorado task force also provide adequate dilution of the crawl space air, especially at the structural floor surface. This is due to the fact that warmer indoor air is used for dilution, thus keeping the temperatures of the surrounding materials higher and the potential for condensation lower. It was also found that the negative pressures created by Case 3 requirements are not significant, approaching 0.5Pa. However, the importance of the placement of floor registers on the dilution was observed in the analysis. The authors would recommend a more stringent spacing requirement, from 1/250ft^2 to 1/200ft^2.

Case 4, no ventilation, does not appear to provide dilution of the crawl space air to maintain relative humidity below the critical 80% threshold. This is due to the lack of natural air exchanges with the exterior, or even basement once the flooring materials are installed. Thus, it is justified to provide dilution of the water vapor through ventilation in addition to a ground cover for deep crawl spaces.

It should be noted that the results of the CFD analysis for below grade underfloor spaces should not be interpreted as absolute, but rather a comparison between methods. For example, Case 4 will not necessarily result in the humidity profiles shown in Fig. 16, but rather Case 2 will provide better humidity control than Case 4. Many factors will influence the humidity control performance for deep crawl spaces, including surface temperatures, natural air leakage, differing evaporation rates for different soil areas, etc. that were not part of this study. Obviously, further analysis is needed but the results can provide some insight into the abilities of various moisture control techniques to manage humidity within deep crawl spaces.

6 Conclusions

The test data confirms that the installation of a ground cover is an effective means to control moisture and consideration in crawl spaces and should be given to a requirement in all building codes, especially due to the low cost of installation versus the benefit.

The simplified estimation method of moisture loads originating from soils below structures by Kurnitski (2001) can be used to provide a reasonable estimate of moisture loads for practicing engineers, if ventilation is not provided. The methodology showed the moisture load from saturated soil is approximately 40 grains/(ft^2·h), which can be used as a design value. Test data showed the outdoor humidity concentration affects crawl space humidity concentrations, and natural air infiltration rate for at-grade crawl spaces in dry climates is sufficient to mitigate the buildup of moisture if a ground cover is used, and significant air leakage occurs between crawl spaces and unfinished basements and the exterior, even when effort is made to prevent this airflow.

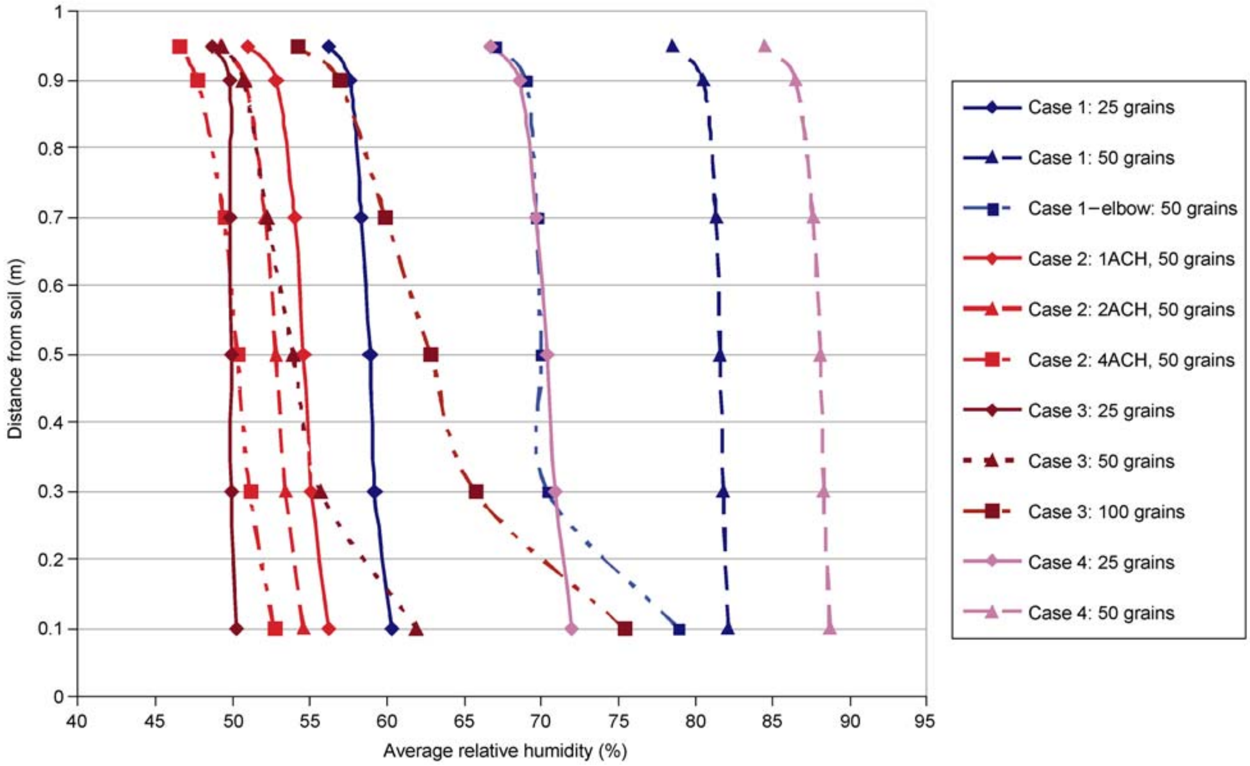

Fig 16 Below grade crawl space CFD analysis results

Practicing building scientists can use CFD software to analyze differing crawl space environmental conditions and ventilation strategies. CFD analysis, supported by test data, suggests that the current building code requirements are adequate for the reduction of moisture in at-grade crawl spaces in non-humid climate; furthermore, sealed or non-vented crawl spaces are preferred over ventilated crawl spaces in humid climates. However, the natural air infiltration rate for below grade underfloor spaces may not be sufficient to prevent the buildup of moisture, even with a ground cover. Additional study into the ventilation and moisture management strategies for below grade underfloor spaces may be warranted.

The recommendations by the Colorado task force for centralized manifold and floor registers are adequate in preventing the buildup of moisture in deep crawl spaces and may not cause backdrafting of combustion appliances if the fan is sized per ASHRAE 62.2 guidelines (ASHRAE 2007).

Finally, building codes should recognize below grade underfloor space ventilation and moisture control, which should have differing prescriptive requirements compared to at-grade crawl spaces.

References

ASHRAE (2007). ANSI/ASHRAE 62.2-2007: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Davis B, Warren WE, Rose WB, et al. (2005). Technology assessment report—A field study comparison of the energy and moisture performance characteristics of ventilated versus sealed crawl spaces in the south. Instrument # DE-FC26-00NT40995, Field Study Final Report to Department of Energy and National Energy Technology Laboratory.

International Code Council (2003). International Residential Code 2003. Delmar Cengage Learning.

Karagiozis AN (2005). A field study comparison of the energy and moisture performance characteristics of ventilated versus sealed crawl spaces in the south-hygrothermal performance study (experimental and modeling) (phase-2). Instrument #: DE-FC26-00NT40995, Prepared for Advanced Energy Corporation by Oak Ridge National Laboratories—Engineering Science and Technology Division.

Krarti M (2000). Energy Audit of Building Systems: An Engineering Approach. Boca Raton, FL: CRC Press.

Kurnitski J (2001). Ground moisture evaporation in crawl spaces. *Building and Environment*, 36: 359 – 373.

Lstiburek J (2004). Conditioned crawl space construction, performance and codes. Research Report 0401 for the US Department of Energy's Building America Program: Systems Engineering Approach to Development of Advanced Residential Buildings. http://www.buildingscience.com.

MMTF (Moisture Management Task Force—Colorado) (2003). Guidelines for design and construction of new homes with below-grade under-floor spaces—version 1.0. http://www.buildwise.org.

Rose WB (1994). A review of the regulatory and technical literature related to crawl space moisture control. In: Recommended practices for controlling moisture in crawl spaces. *ASHRAE Technical Data Bulletin*, 10(3): 5 – 17.

Sherman MH, Grimsrud DT (1980). Infiltration-pressurization correlation: Simplified physical modeling. *ASHRAE Transactions*, 86(2): 778 – 803.

Trethowen HA (1994). Three surveys of subfloor moisture in New Zealand. *ASHRAE Transactions*, 100(1): 1427 – 1437.

Viitanen H, Salonvaara M (2001). Failure criteria, MNL40. In: Trechsel H (ed), Moisture Analysis and Condensation Control in Building Envelopes (Chapter 4, pp. 66 – 80). West Conshohocken, PA, USA: ASTM.

Zhai Z (2006). Applications of CFD in building design: Aspects and trends. *Indoor and Built Environment*, 15(4): 305 – 313.