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NUMERICAL ANALYSIS OF HEAT STORAGE AND HEAT CONDUCTIVITY IN THE CONCRETE HOLLOW CORE DECK ELEMENT

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ABSTRACT

In order to minimize energy used for cooling and heating, one of the passive solutions is to efficiently utilize heat storage of a building construction. Presently, heat storage calculations in whole building simulation programs are based on 1D heat transfer models. This paper investigates to what extent these simplified models estimate the heat storage potential of precast hollow-core concrete decks correctly. This study investigates various approaches on how to model the heat transfer within the air void in the deck. Furthermore, it is analysed how different heat transfer models influence the overall heat transfer and heat storage in the hollow-core decks.

The presented results allow comparison between detailed results from 2D-COMSOL simulations and simple 1D calculations from the whole building simulation tool such as BSim program and moreover, it is possible to validate the calculation method in BSim for the concrete deck element with air voids.

Finally, this paper presents a comparison of the calculated heat conductivity of the hollow-core concrete deck and the measured heat conductivity for the same deck by using hot box apparatus.

INTRODUCTION

The building simulation tools, which are currently being applied, are exceptionally useful and very important when buildings' energy use and indoor climate need to be foreseen. However, it is always a challenge to precisely reflect a real life condition and obtain reliable results when using whole building simulation programs. As a consequence of poor modeling, the incorrect and inefficient HVAC system can be selected and poor indoor climate achieved. The same concerns utilization of passive technologies such as, for example, day light utilization, heat storage, passive cooling and heating. On the contrary, correct simulation can highlight possible energy savings and improvements in the indoor thermal environment.

Generally, in well designed buildings, energy use and indoor climate are dependent on each other and usually, the final effect is a compromise between one and another. At the modeling stage of the building, these two parameters are dependent, among other factors, on stationary and transient thermo-physical parameters of materials used for construction.

Normally in simulation programs, such as for example BSim, construction elements are defined as one homogeneous layer or combination of homogeneous layers with defined density, thermal conductivity and specific heat capacity. Knowing these thermal properties of the construction materials allows performance of transient simulations which considers heat storage. In the building simulation, concrete construction elements are usually defined as homogenous and isotropic materials. Additionally, many building simulation programs consider constructions, as 1-D elements, in order to decrease simulation time and become more time efficient. This means that possible inhomogenities within one layer, such as air voids, are not taken into consideration, although they might have a significant influence on the heat storage calculation of the building.

During the past years, several studies have been done on thermal behavior of hollow-core concrete slabs. A theoretical study (P. Gandhidasan, 1985) indicated that heat flux, which enters through the roof, made of hollow-core concrete slabs is independent of location of air cavity within the depth of the slab. However, the study presents a one dimensional approach to the problem without including the complexity of thermal bridges through the air cavity. Additionally, the air cavity is considered as a uniform cavity that separates the outer and inner layer of the concrete. Therefore, the model does not sufficiently present the thermal conditions within the hollow-core concrete slab presented in Figure 1 and thus, it cannot be used as a methodology to calculate this type of construction in the whole building simulation programs.

Another approach was presented in (Z.L. Zhang, 2009) where a model of a hollow-core concrete slab was created in the COMSOL program in order to study heat transfer and the heat storing capacity in the concrete elements with air cavities. However, in the research presented by (Zhang), the focus was on investigation of how the cavity area influences heat storage of the deck. This paper's focus is on various heat transfer mechanisms within the air void in the deck and on validation of a simplified model for whole building simulation tool. Moreover, it is investiagted if heat transfer by convection and radiation within the air void is an important parameter that strongly influences the overall heat transfer and overall heat storage of the hollow-core deck element.

The first objective of this study is to investigate various approaches on how to model the heat transfer in the slab with the air voids. This is done by creating steady- state 2D models of the hollow-core concrete deck using the COMSOL program. Secondly, the 2D model is simplified to be presented as a 1D model. Two various approaches are considered when simplifying the 2D model into a 1D model in COMSOL; 1D-one layer model and 1D-three layer model. Thirdly, results from the steady-state 2D modeling of heat conductivity are used to calculate equivalent thermal conductivity in 1D models. Furthermore, equivalent thermal conductivity is used to find equivalent thermal mass of the the hollow-core deck element presented by the 1D models. This part of the investigation ends with comparison of calculated diurnal heat storage of the deck for the 2D COMSOL model, 1D-one layer and 1D-three layer COMSOL model and the 1D-COMSOL model callculated according to the present BSim methodology for simulating hollow-core decks.

Afterwards, the calculation methodology of heat storage in the hollow-core concrete deck in BSim is validated based on results from the 2D COMSOL detailed simulations.

Finally, this paper presents the measured thermal conductivity of the hollow-core deck when using hot box apparatus. The intention is to define which of the approaches to calculate heat transfer is the closest to the real life condition and to state how important proper assumption is to simulate heat transfer within the air void in the hollow-core deck.

The paper is finished with discussion and conclusion.

SIMULATION

This paper presents computational and experimental investigations. The numerical model that was created in the COMSOL and BSim program was based on the real cast of the hollow-core concrete deck element which is presented in Figure 1 in section view.

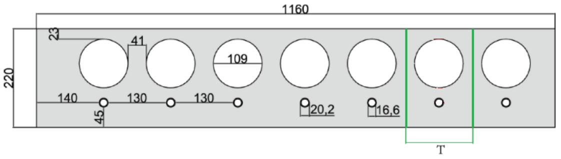

Figure 1 Section view of hollow-core deck.

Thermal properties of the concrete used in COMSOL are assumed to be as follows: thermal conductivity 1,8 [W/m^{2}K], density 2300[kg/m^3] and specific heat capacity 1000 [J/kgK]. In order to save simulation time and due to symmetry of the element, only one section “T” presented in Figure 1 is modelled. The model presented in Figure1 was used for both steady-state and transient simulations.

The small circular voids that can be seen on the bottom of the deck represents water pipes that were used in another experiment where the deck was thermally activated. Due to the small size of these pipes, they only have a minor importance on the experimental investigation of thermal conductivity. In the modeling part, they were not included in the model and substituted by the concrete material.

Steady-state simulation

For the steady-state models, the temperature on the upper and lower surface of the deck is presented as a constant temperature and the temperature on the bottom is different from the temperature on the top of the deck.

Heat transfer within the air void is modelled according to the following four various assumptions:

1. Air void is presented as an adiabatic boundary.

2. Air in the void is given real air thermal properties such as: density, thermal conductivity, specific heat capacity. However, air is standing still thus no convection is considered. In this model, radiation between surfaces is not considered.

3. Air void cavity is given radiation surface to surface boundary.

4. Air void is given equivalent thermal conductivity calculated based on norm [DS EN ISO 10077-2, 2004]. This thermal conductivity considers heat transfer by convection and radiation in closed voids.

In this study, parametrization of the heat transfer within the air void is distributed along with 4 various assumptions presented above in this section. In the first model, the air void is excluded from the heat transfer through the slab with air voids, in the second model, the air void is included in the heat transfer through the slab but neither convection nor radiation is considered. The third model considers only heat transfer by radiation between air void surfaces and in the fourth model, both radiation and convection in the air voids is included.

During the steady-state simulations, firstly, the 2D models were calculated as per assumption given in points 1 to 4 in this section. Afterwards, the 2D models were simplified to 1D models as presented in Fig. 2.

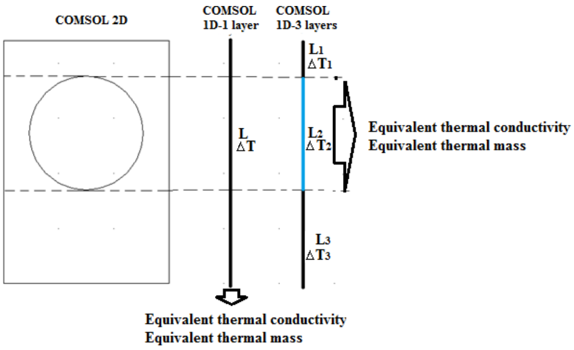

Figure 2 Transformation of 2D model into1D model.

The 2D model is represented by 1D one-layer model and 1D three-layer model. As stated in (Zhang), for the 1D one-layer model, equivalent thermal conductivity λ^e can be calculated directly from the 2D model. For the 1D three-layer model, the length of the layer with the void is calculated as $L_2 = L-(L_1+L_3)$, see Figure 2. The thermal conductivity for layer L_1 and L_3 is taken as the value of bulk concrete λ_c = 1,8 [W/m^{2}K]. Then equivalent thermal conductivity of layer L_2 can be calculated as:

$$\lambda_2^e = L_2 \times \alpha_2 = L_2 \times \frac{\alpha}{1-\frac{\alpha}{\alpha_1}-\frac{\alpha}{\alpha_2}} \qquad (1)$$

Where $\alpha=\lambda^e/L$, $\alpha_1=\lambda_c/L_1$, $\alpha_3=\lambda_c/L_3$ and for steady-state condition can be written that:

$$\alpha_1 \times \Delta T_1= \alpha_2 \times \Delta T_2= \alpha_3 \times \Delta T_3= \alpha \times \Delta T \qquad (2)$$

Where: $\Delta T=\Delta T_1+\Delta T_2+\Delta T_3$

Transient simulation

For the transient simulation, total heat transfer coefficient on the upper and lower surface of the deck is given as 8 [W/m^{2}K]. The total heat transfer coefficient represents both heat transfer by convection and radiation.

In transient simulation, a diurnal temperature fluctuation on the upper and lower side of the deck is represented by the sin curve varying from 20 to 26^{0}C. To reach quasi steady-state, each simulation is run for 5 days and results are taken from the last day.

BSim simulation

In the BSim program, two approaches for calculating the heat storage of the hollow-core deck element were investigated. The first one (in this paper called “BSim methodology”) is implementing existing methodology suggested in the BSim program, see Figure 3 and Equation 3. The second one, (in this paper called “BSim reference”) is utilizing findings obtained from transformation of the 2D model of hollow-core deck element into a 1D three-layer model, which, as displayed in Figure 6 and 7, gives very good results. In the second method, equivalent thermal conductivity for layer with air void was taken from the 1D three-layer model where air void is simulated as air standing still (see section steady-state simulation). The reason for this apporoach is that the heat transfer is probably closest to the methodology presently valid in the BSim program which was developed along with development and validation of calcualtion method for the heat transfer in water-based radiant systems (M. Scarpa et al., 2009).

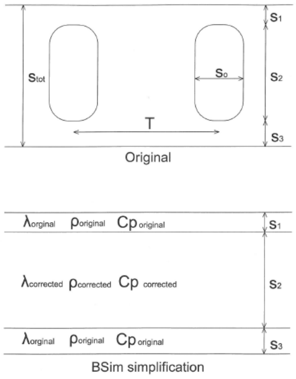

Figure 3 BSim simplification of hollow-core deck.

$$\lambda_{corrected}= \lambda_{original} * (T-s_0)/T$$
$$\rho_{corrected}= \rho_{original}*(T-s_0)/T \qquad (3)$$
$$Cp_{corrected}= Cp_{original}$$

Where: λ is thermal conductivity [W/mK], ρ is density [kg/m³] and Cp is specific heat capacity [J/kgK].

Equivalent thermal mass used in the BSim reference model was chosen in order to give the same diurnal heat storage as calculated for the transient 2D model with air void simulated as standing still air and is determined with use of Figure 6.

EXPERIMENT

Experimental investigation of thermal conductivity of hollow-core concrete deck element

The purpose of experimental investigation of the thermal conductivity of the concrete hollow-core deck element is to estimate which of the modeling assumption for the heat transfer within the air void is closest to the real life conditions.

To measure the thermal conductivity of the deck, a guarded hot box apparatus is used, see Fig. 4.

Presented in Figure 4, the hot box apparatus has a sandwich wall construction made of: 10mm MDF plate, 300 mm EPS and again 10 mm MDF plate. Metering box has walls constructed as following: 10 mm MDF and 40 mm EPS.

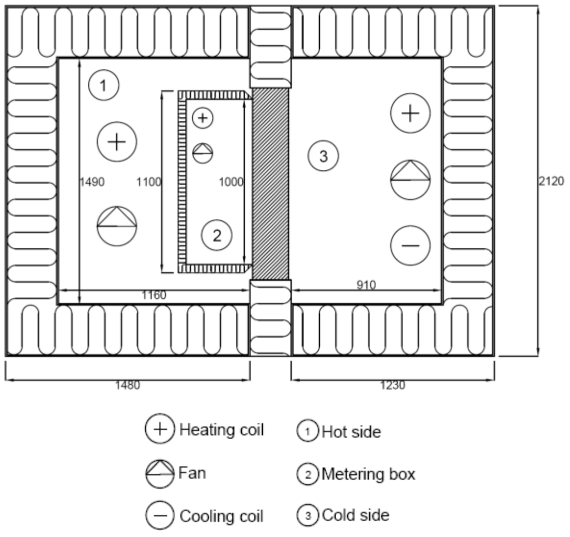

Figure 4 Set up of the deck in the hot box, vertical section.

The concrete deck is inserted between the hot and cold side of the deck. Secondly, the air temperature on the hot and cold side is stabilized, see Figure 5. Additionally, necessary time is taken untill the air temperature between the hot side and the metering zone stabilizes and reaches equilibrium. If this happens, it is known that all energy, (which is measured), provided to the metering box is transfered through the deck to the lower temperature in the cold zone.

In order to calculate the thermal conductivity of the deck, a heat supply to the guarding box was measured by a watmeter. Surface temperature of the deck on the hot and cold side was measured with 6 thermocouples type "K" on each side of the deck. Temperatures were logged by the data logger Fluke Helios Plus 2287A.

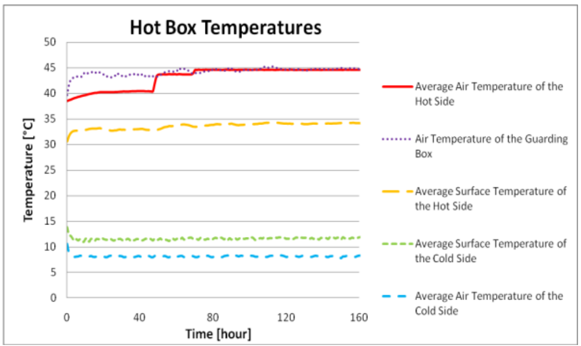

Figure 5 Temperature stabilization in hot box apparatus.

RESULTS

2D heat transfer calculation

In Table 1, the results of the obtained thermal conductivity for the 2D models from COMSOL simulations are presented, where the results are the average values for the entire deck.

Table 1. Overall heat transfer in the hollow-core deck modelled as 2D model.

HEAT TRANSFER WITHIN AIR VOID	λ
[-]	[W/mK]
Air void: adiabatic	0,982
Air void: standing still air	1,002
Air void: radiation	1,246
Air void: equivalent conductivity	1,261

Equivalent thermal conductivity of 1D-one layer models

The calculated results of thermal conductivity from the simulation analysis of the 2D models presented in Table 1 are exactly the same for equivalent thermal conductivity of the 1D one-layer model. For the 1D tree-layer model, equivalent thermal conductivities of layer L_2 with air cavity were calculated according to Equation 1. For the four considered cases, results are presented in Table 2.

Table 2. Heat transfer of the layer with the air void in the hollow-core deck modelled as 1D three-layer model.

HEAT TRANSFER WITHIN AIR VOID	λ^e
[-]	[W/mK]
Air void: insulation	0,648
Air void: standing still air	0,666
Air void: radiation	0,923
Air void: equivalent conductivity	0,941

Equivalent thermal mass-transient simulation

In order to be able to properly calculate thermal storage with the use of 1D models, it is necessary to find proper thermal mass of the layer with air cavities. This adjustment can be done by varying either material density or specific heat capacity. In this study, it was chosen to vary material density.

In the transient simulation of 1D one-layer model for the study presented in this paper, which is for void simulated as standing still air, the thermal conductivity is taken from Table 1.Then thermal mass is varied from 2100 to 4500 [J/m^{3}K] by varying material's density, see Figure 6.

In the transient simulation of 1D three-layer model, for the study presented in this paper, which is for void simulated as standing still air, the thermal conductivity is taken from Table 2. Then thermal mass is varied from 1000 to 2500 [J/m^{3}K] by varying material's density, see Figure 6.

Results of heat stored for the 1D one-layer model and the 1D three-layer model are compared with heat storage obtained from the 2D simulation analysis. Obtained heat storage for the 2D analysis is a value and not a function of thermal mass, however, it was depicted in the Figure 6 and 7 as a line. The purpose is to illustrate equivalent thermal mass for the 1D models that will give the same heat storage as from the 2D simulation. Another condition is that in 1D models an equivalent thermal conductivity is applied.

The vertical blue line represents the decks actual thermal mass which was callculated based on known decks geometry.

A purple dot represents heat storage calculated by the COMSOL but according to the BSim methodology for calculating hollow-core decks, see Equation 3.

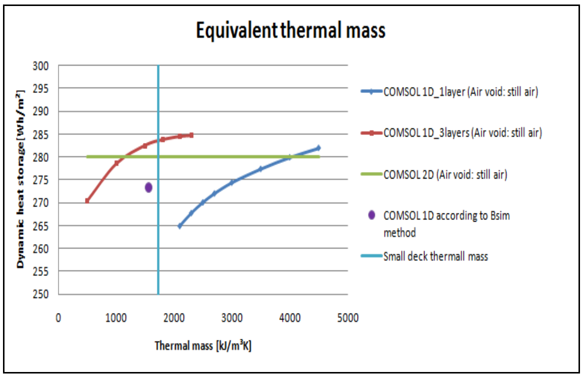

Figure 6 Calculation of equivalent thermal mass.

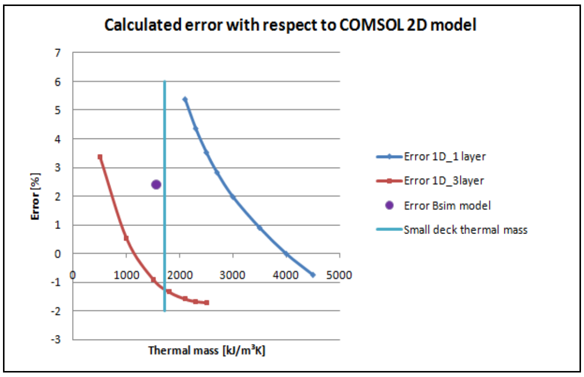

Figure 7 Calculated error of heat storage in function of equivalent thermal mass.

Validation of BSim heat storage calculation methodology for hollow-core concrete deck

Results from the investigation, presented in the previous section, indicate that the 1D three-layer model should be much more accurate than the 1D one-layer model. This also fits with the methodology used in the BSim program.

The reference 2D model of the concrete hollow-core deck element was created in COMSOL Multiphysics to validate heat storage calculation of inhomogeneous construction elements in the BSim program. In this investigation, the simulation of the deck is parameterised by the heat transfer coefficient on the bottom and top surface of the deck and this heat transfer coefficient varies from 4 to 30 [W/m²K].

Dynamic heat storage capacity for each parameterised heat transfer coefficient on the surface is calculated as integral of diurnal normal total heat flux.

Results from this investigation are presented in Figure 8 and 9.

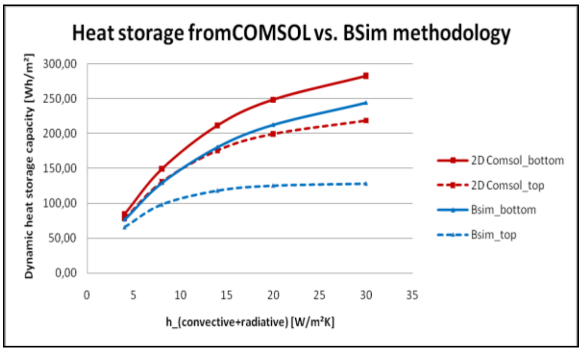

Figure 8 Validation of calculation methodology for heat storage in BSim.

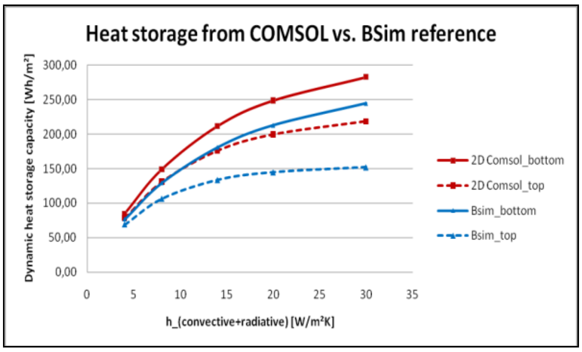

Figure 9 Validation of improved calculation methodology for heat storage in BSim.

Table 3. Calculated difference between heat storage obtained from 2D COMSOL and respectively model "BSim methodology" and "BSim reference."

H	ERROR "BSIM METHODOLOGY"	ERROR "BSIM REFERENCE"
[W/m²K]	[%]	[%]
4	13,8	12,3
8	21,9	18,9
14	28,9	23,3
20	32,3	25,3
30	35,2	26,4

Error in Table 3 is given with respect to the results from the 2D COMSOL models and is calculated for sum of heat flux on the bottom and on the top of the deck.

Experimental determination of the thermal conductivity of the hollow-core deck element

The thermal conductivity was calculated after temperatures had been stabilized, see Figure 5. Thermal conductivity was calculated for two various temperature setups, see Table 4.

Table 4 Measured thermal conductivity of hollow-core concrete deck.

SETUP	THERMAL CONDUCTIVITY
[-]	[W/mK]
1st	1,50
2nd	1,52
Average:	1,51

DISCUSSION

Based on the results from the COMSOL 2D steady-state simulations, it can be observed that for the first two cases, where the air void is represented by adiabatic boundary and respectively air standing still, the obtained thermal conductivity is almost the same. These results are in agreement with expectations because standing still air has very poor thermal conductivity and it can be considered as a good insulator.

The following two cases, where heat transfer within air void in the first case is including surface to surface radiation and in the second equivalent thermal conductivity that includes convection and radiation, gave considerably higher thermal conductivity than the first two cases. These results and the fact that the model with equivalent conductivity gives highest thermal conductivity of the deck comply with the expectations.

The same dependence can be observed for the calculated equivalent thermal conductivity, see Table 2, for 1D-three layer model.

Results from investigation of equivalent thermal mass presented in Figure 6 indicate that the 1D-three layer model is much more accurate than the 1D-one layer model. For the 1D-three layer model, error with respect to the 2D model is only 1,2% and for the 1D-one layer model, it is higher than 7% at the real decks thermal mass, see Figure 7. Furthermore, results indicate that for the 1D one-layer model , it is necessary to use very high equivalent thermal mass in order to obtain heat storage that is close to the reference 2D calculation.

As presented in Figure 6, results from the COMSOL 1D model that calculates according to BSim method are in agreement with the COMSOL 1D-three layer model and with the COMSOL 2D model.

It can also be noticed that with respect to the COMSOL models, the BSim methodology is slightly underestimating thermal mass and also heat storage capacity of the hollow-core deck element.

Figure 8 presents results of validation of calculation methodology of dynamic heat storage capacity in BSim. Heat storage is presented as a function of heat transfer coefficient on the surface of the deck. The heat storage was presented separately for the heat flux on the top and on the bottom of the deck. It can be observed that the higher heat transfer coefficient on the surface, the bigger the discrepancy is between BSim and reference 2D COMSOL results. In Figure 9, methodology for presenting results was preserved from Figure 8. It can be observed that results presented in Figure 9 indicate improvement with regards to results presented in Figure 8, however, especially for high heat transfer coefficients. All in all, discrepancies between both presented BSim methods "BSim methodology" and "BSim reference" and COMSOL reference results are high. These results indicate that any simplification of heat transfer in inhomogeneous construction, such as hollow-core slab from 2D to 1D can result in deformation of results. Moreover, it can be observed that when applying BSim methodology into COMSOL, see Figure 6 and 7, error of calculated dynamic heat storage with respect to detail 2D COMSOL model is of only approximately 2,5% for heat transfer coefficient on the surface of 8 [W/m^2K]. On the contrary, the same BSim methodology but calculated in BSim and compared with detail 2D COMSOL model and for heat transfer coefficient on the surface of 8 [W/m^2K] gives discrepancy of 21,9%, see table 3.

Finally, results presented in Table 4 are valid for thernal conductivity obtained from the measurements. With respect to simulation results, it can be observed that the model which include heat transfer by coanvection and radiation within the air void is the closest to the results obtained from the experiments.

Based on the obtained results, it can be concluded that BSim methodology for calculating equivalent thermal conductivity for hollow-core deck element might underestimate this parameter and thus underestimate dynamic heat storage of this type of building construction.

CONCLUSION

The simulation results indicated that 1D-three layer model is better aproximation of the hollow-core deck than 1D-one layer model.

The validation of heat storage calculation ín BSim indicated that disagreement with reference COMSOL model is high, see Figure 8 and 9. Furthermore, the high disagreement is not due to inaccurate simplification of the 2D inhomogeneous hollow-core deck element into 1D model as presented in Figure 6 and 7 but due to other numerical reasons that need to be clarified.

It can be also observed that the disagreement of the heat storage is mainly due to the discrepancy of the heat flux on the upper surface of the deck. This can be explained by the air void closer location to the upper surface of the deck. The discrepancy would be minimized if the deck was simulated with the floor. Therfore, it is recommended to take a real design of the internal flooring into consideration. As a consequence of the revealed results, a closer look into the heat storage calculation mothod in BSim will be given.

Finally, when comparing obtained thermal conductivity of the hollow-core deck for various modeling assumptions regarding heat transfer in the air void, it can be observed that the overall deck thermal conductivity varies from 0,98 to 1,26 [W/mK]. This variation is rather substantial and indicates that proper modeling of the heat transfer within the hollow-core deck element might be crucial to properly calculate the heat storage in this type of building construction element.

To sum up, the discrepancy between measured and simulated thermal conductivity can not only be due to various approaches to modeling heat transfer within closed air void but also due to different thermal counductivity of bulk concrete that was assumed in the simualtion models and that is in the deck used in the experiment. Moreover, the simulation model does not include steel reinforcement that is located in the deck and which should have an impact on the overall thermal conductivity as it has larger thermal conductivity than pure concrete.

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