THE ENERGY PERFORMANCE OF THE COLD-FORMED STEEL-FRAME AND WOOD-FRAME HOUSES DEVELOPED FOR THAILAND

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ABSTRACT

This paper presents the energy consumption of a two-storey detached house in Thailand constructed by three different systems: concrete-frame house, steel-frame house, and wood-frame house. The EnergyPlus software was used to simulate the energy performance of the houses. Different methods for simulating framing construction were compared in order to choose the appropriate one. The energy consumption of the houses was then investigated based on the selected method. The construction cost and electricity cost of different types of houses were analyzed to determine the economical system.

INTRODUCTION

In Thailand, most houses are constructed by concrete frame (reinforced concrete columns and beams) with brick walls. Wood-frame and cold-formed steel-frame construction have been applied for the house construction in Thailand for more than 10 years. Although the wood-frame and lightweight steel-frame house construction are widely used in other countries such as the United States and Canada, they are sparsely used for house construction in Thailand. However, recent research has shown that the steel-frame house construction has become more acceptable than in the past. The results of the questionnaires regarding the attitudes of the visitors toward the demonstrated steel-frame house constructed at the annual Architect Expo '03 show that 68% of the subjects are interested in buying this type of house if the price is within ±15% of the price of a conventional concrete-frame house (Puvanant et al. 2003).

Previous research has shown that thermal bridges caused by wood or steel framing affect thermal performance of assemblies. The methods for evaluating the thermal resistance of the wood-frame and steel-frame assemblies have been studied in several research (Kosny and Christian, 1995; Trethowen, 1995; Tulaca et al. 1997). The energy performance of the steel-frame and wood-frame houses have been investigated and compared with other construction systems (SIP, ICF, etc.) either by constructing real houses at the same location and measuring energy consumptions (NAHB, 1999; NAHB, 2002) or by using simulation tools (NAHB, 1999; Gajda, 2001; Purdy and Beausoleil-Morrison, 2001; Doebber, 2004; Kosny, 2004).

Several methods have been utilized to model wood-frame and steel-frame houses in the energy simulation programs. These include a simplified method which disregards the effect of studs (model only a center of cavity wall) and more advanced methods which take the effect of the thermal bridges caused by wood or steel frames into account. The research seeks to explore the differences of the results calculated by each method. The results would help to decide which method should be utilized when the level of accuracy or the effort is taken into considerations

Although there are many researches on energy performance of wood-frame and steel-frame houses, those researches were conducted in different weather conditions and with different construction materials from those used in Thailand. The energy performance of the wood-frame and steel-frame houses need to be further investigated in order to develop these construction systems to suit appropriately the house constructions in Thailand.

This paper consists of two main parts. The first part is to compare the results of the different methods applied for modeling the wood-frame and steel-frame houses in EnergyPlus. The second part is to compare the construction cost and energy cost of the concrete-frame, wood-frame, and steel-frame houses in order to determine which house is the most worthwhile to construct.

HOUSE DESCRIPTION

The house for this study is a two-storey detached house (Figure 1) designed in the research of Puvanant et al. (2004). The total space of the interior and exterior is 196 m^2 and 48 m^2 respectively. The first floor is composed of a living room, bedroom, dining room, kitchen, pantry, bathroom, and stairs. The second floor has three bedrooms, multipurpose room, and two bathrooms. The front of the house faces the south. It was assumed that the house will be constructed in the suburb area of Bangkok. Details of the building components (exterior walls, interior walls, floors, ceilings, and roofs) of the concrete-frame, wood-frame, and steel-frame houses are shown in Table 1.

Figure 1. Case study house

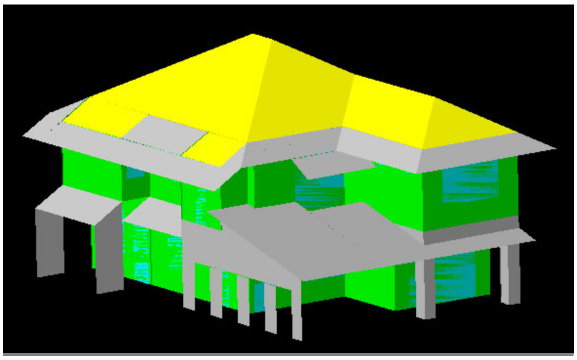

Figure 2. Case study house modeled in EnergyPlus

SIMULATION INPUT

The house modeled in EnergyPlus has 18 thermal zones. The first floor has eight thermal zones, the second floor has nine thermal zones, and the roof has one zone. The house has five occupants. The lighting for each zone was based on the lighting design shown in the construction drawings (average 4.5 W/m^2). Electrical equipments are based on appliances presented in a typical house. The infiltration rates of three houses are 0.5 ACH which is the same rate for every zone.

Only six zones (living, multipurpose, and four bedrooms) have air conditioners due to the hot weather almost all year round in Bangkok. The schedules of turning the air conditioners on for each zone were: bedroom, 9 pm – 6 am on weekdays and 9 pm - 7 am on weekends; living room, 1 pm – 9 pm everyday; multipurpose room, 7 pm – 10 pm on weekdays and 1 pm – 11 pm on weekends. The conditioning components were modeled by using the "Purchased Air" components provided in the EnergyPlus. The purchased air is the simplest piece of the zone equipment that can supply heating or cooling air according to the specified conditions (temperature, air humidity ratio) to meet the zone heating or cooling load (DOE, 2005). For this study, the purchased air components were modeled without any limit on cooling supply air flow rate. The temperature set points were 25 ^{o}C. The weather data of Bangkok was used for the simulation (THA_Bangkok_ IWEC.epw). The house modeled in EnergyPlus is shown in Figure 2.

METHODS USED FOR MODELING WOOD- AND STEEL-FRAME HOUSES

The main objective of the method comparison is to find out the differences in the results (cooling loads and temperatures) calculated by each method when compared with the one that most accurately represents the frame assembly. The results will help to decide the appropriate method to be use for the study. The five methods (Figure 3) for modeling the wood-frame and steel-frame houses in order to compare their results are:

1. Without stud: Only the part of the wall without stud (center of cavity wall) was modeled. This method was used in the comparison because it is the simplest way to model when the effect of studs is not taken into account.

2. Only wall R-value: For this method, the effect of the wood or steel frames on the thermal resistance of a wall is taken into account but the effect of the thermal mass is disregarded. The wall R-value was calculated by THERM 5.2, a two-dimensional conduction heat transfer analysis software based on the finite element method (Finlayson et al. 1998). The wall construction input in the EnergyPlus has one or two material layers (Material:R). Two layers are needed if the surface properties (roughness, thermal absorptance, solar absorptance, visible absorptace) of the interior and exterior surfaces are different. The EnergyPlus simulates the material-R as steady state heat conduction (DOE, 2005).

3. With and without studs: For the wall, two surfaces were modeled. The first part represents the part of the wall without stud and was modeled as a base surface (Surface:HeatTransfer) in the Energyplus. The second part rerspresents the part of the wall having stud and was modeled as a subsurface (Surface:HeatTransfer: Sub), whose surface type is "Door." The advantage of modeling this part of the wall as a subsurface instead of a base surface is that when a stud size is changed (such as from wood stud to steel stud) only the subsurface geometries are needed to be adjusted.

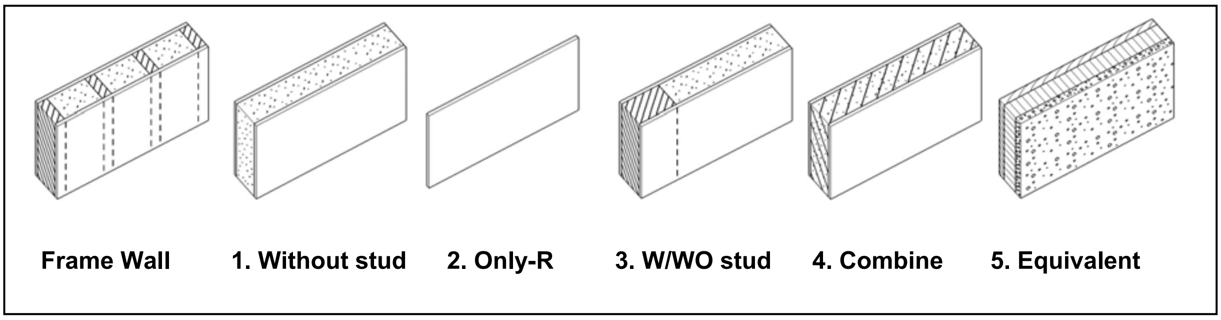

Figure 3. Five methods for modeling a frame wall

The total area of the subsurface was calculated according to the stud size and spacing. If the wall has windows or doors, the parts of the missing studs are also subtracted from calculation. The steel stud was modeled in a rectangular shape with the same width as the stud flange and the same height as stud web. We used the density value of the steel and adjusted the specific heat value so that the thermal mass was equal to the real stud shape.

The thermal resistance of the steel stud was calculated by dividing the steel stud into several parallel layers perpendicular to the heat flow direction (Figure 4). The thermal resistance of each layer was calculated and added up to obtain the total thermal resistance. All subsurfaces are located on the left side of all base surfaces. Placing the subsurfaces on different positions of the base surfaces affects the cooling load but the effect is very small. This method does not require the result (R-value) from the two-dimensional heat transfer program. It does not take the effect of the thermal bridge caused by the studs into account. In addition, the number of the surfaces input doubled, therefore, it took longer for the data input and simulation.

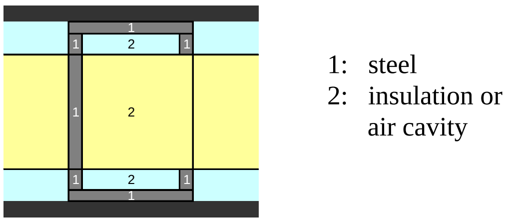

Figure 4. Dividing steel stud section for R-value calculation

4. Combine thermal properties: This method is adapted from (Purdy and Beausoleil-Morrison, 2001). THERM is utilized to calculate the R-value of the frame wall. The material properties of the layer which has stud and insulation was adjusted by changing its thermal conductivity so that the total thermal resistance of the wall construction is equal to the thermal resistance calculated by THERM. The thermal properties (density, specific heat) of this layer was also adjusted to combine the thermal mass of the studs and the insulation. For this method, the effects of studs on the thermal resistance and the thermal mass of the wall were taken into accounted. However, the wall with the combined thermal properties might not have the same thermal performance as the real one.

5. Equivalent Wall: This method has been cited in several literatures (Carpenter, 2001; Enermodal et al., 2001; Kosny and Kosseca, 2002). The equivalent wall has "*a simple one-dimensional multi-layer structure and the same thermal properties as the actual wall (total resistance and thermal capacitance). Its dynamic thermal behavior is identical to the actual wall*." (Enermodal et al., 2001:3). A process to generate "equivalent wall" is rather complicated compared to the aforementioned methods. However, once the "equivalent wall" thermal properties are derived, modeling in the EnergyPlus is easier than the third method which requires the data input of two surfaces for each wall. The "equivalent wall" method has been utilized to represent several wall construction systems such as wood-frame wall, precast concrete panel, and insulating concrete form (Kosny and Kossecka, 2002; Doebber, 2004).

THERM was used to calculate data needed for calculating thermophysical properties of the "equivalent wall." The data calculated by THERM are the thermal resistance of an assembly, and dimensionless temperature for the problem of steady-state heat transfer (exterior temperature = 1 and interior temperature = 0). A spreadsheet program was developed to integrate all the dimensionless temperature, density, and specific heat of each wall element according to the formulas for deriving "thermal structure factors" written in the report (Enermodal et al., 2001). An "equivalent wall generator", a computer program included as a part of the report, was then utilized to calculate the thermophysical properties for each layer of the "equivalent wall" so that the total thermal capacitance, thermal resistance, and thermal structure factors of the "equivalent wall" are identical to those which were input in the program.

Table 1. Details of the houses' components

BUILDING COMPONENT	CONCRETE	WOOD FRAME	STEEL FRAME
1. Exterior walls	brick wall 100 mm	wood cement board 12 mm wood stud 50x100 mm @ 600 mm. fiber glass 50 mm in stud cavity gypsum board 12 mm	wood cement board 12 mm steel stud 92x45x0.08 mm @ 600 mm fiber glass 50 mm in stud cavity gypsum board 12 mm.
2. Interior walls	brick wall 100 mm	gypsum board 12 mm wood stud 50x100 mm @ 600 mm gypsum board 12 mm	gypsum board 12 mm steel stud 92x45x0.08 mm @ 600 mm gypsum board 12 mm
3. Ground floor	concrete 100 mm granite 12.7 mm	concrete 100 mm granite 12.7 mm	concrete 100 mm granite 12.7 mm
4. Second floor	concrete 100 mm wood floor 12.7 mm	wood joist 50x200 mm @ 600 mm wood cement board 24 mm wood floor 12.7 mm	steel joist 200x45x1mm @ 600 mm wood cement board 24 mm wood floor 12.7 mm
5. Ceilings (below roof)	50 mm fiberglass insulation covered with aluminum foil gypsum board 9 mm	50 mm fiberglass insulation covered with aluminum foil gypsum board 9 mm	50 mm fiberglass insulation covered with aluminum foil gypsum board 9 mm
6. Roof	concrete cement tile	concrete cement tile	concrete cement tile
7. Windows	clear glass 6 mm	clear glass 6 mm	clear glass 6 mm

The "equivalent wall" method takes all factors affecting the thermal performance (thermal resistance, thermal mass, and thermal structure) into account. Therefore, it was used as the main method to be compared with the other four methods. Table 2 shows the thermal properties of all assemblies derived from the other four methods compared with the equivalent wall method.

Table 2. Thermal properties of assembly modeled with four methods compared with those of equivalent wall method

METHOD	R-VALUE	THERMAL MASS
1. Without Stud	✕	✕
2. Only R-value	✔	✕
3. W/WO Stud	✕	✔
4. Combine	✔	✔
5. Equivalent Wall	-	-

✔ value is equal to equivalent wall

✕ value is not equal to equivalent wall

For all surfaces modeled by all methods, the surface properties (roughness, thermal absorptance, solar absorptance and visible absorptance) values for the exterior and interior layers are the same. The thermal resistance of the air cavities were drawn from the results calculated by THERM. The reason for not using the R-value of the air from other sources is to exclude the effect of the material property difference (R-value of air) on the cooling loads and temperatures calculated by each method.

The building components (exterior walls, interior walls, second floor, and ceilings under roof) were modeled differently according to the mentioned methods. The ground floor (concrete slab), and roof were modeled by simple multilayer constructions. Although, research has shown that the interface details have an impact on the thermal performance (Kosny and Desjarlais, 1994; Christian and Kosny, 1996; Kosny et al. 1998), for this study only clear walls were modeled. The envelope interface details (wall corners, wall/roof, wall/floor, wall/door, and wall/window) are not modeled.

DISCUSSION AND RESULTS ANALYSIS [1]

Table 3 and Figure 5 show the differences in the cooling loads calculated from the five methods. The cooling load of the house based on the combined-property method is close to that of the "equivalent wall" method with an average difference of 0.39 %, followed by the W/WO stud method (1.13%), and the without stud method (1.55 %). The second method (only-R-value) gives the greatest different results, about 19 %, from the equivalent wall method.

Figure 6 and 7 show the differences in temperatures calculated based on five different methods. The temperature data is the temperature of the bedroom zone (cooling setpoint 25 ^{O}C from 9 pm - 7 am) in summer, April 15. For the without stud, W/WO stud, and combined-property methods, the temperature differences (ΔT) range from 0.010 to 0.668 ^{o}C. The only-R method gives the greatest temperature differences, with the maximum of 7.3 ^{o}C for the wood-frame house and 6.4 ^{o}C for the steel-frame house.

Table 3. Percentage difference of the cooling loads simulated by EnergyPlus based on different methods

METHOD	WOOD FRAME (%)	STEEL FRAME (%)	AVE-RAGE (%)
1. Without Stud	-1.99	1.11	1.55
2. Only R-value	-20.21	-18.37	19.29
3. W/WO stud	-0.85	1.41	1.13
4. Combine	0.34	0.44	0.39
5. Equivalent	-	-	-

Percentage difference = ((cooling load calculated by other method - cooling load calculated by equivalent wall method) / cooling load calculated by equivalent wall method) x 100.

Average = (|% difference of wood frame| + |% difference of steel frame|) / 2

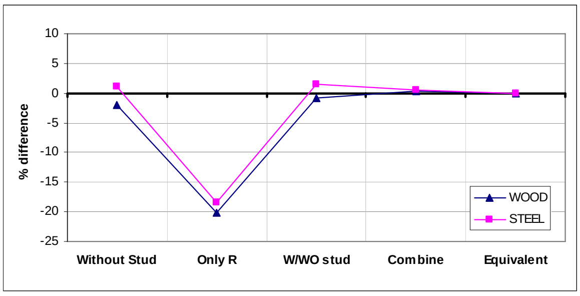

Figure 5. Percentage difference of cooling load calculated based on five different methods

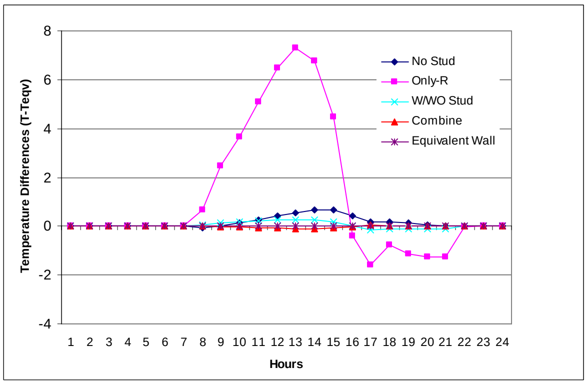

Figure 6. Temperatures' difference calculated by five methods (wood-frame house)

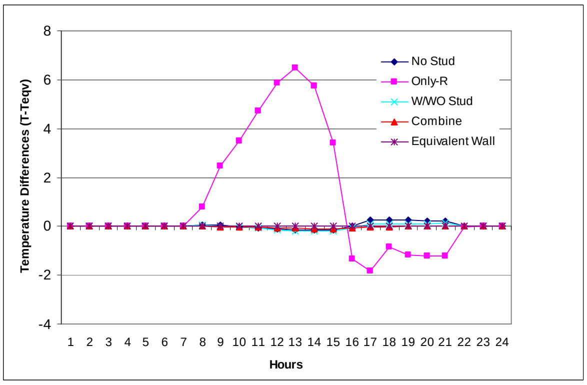

Figure 7. Temperatures' difference calculated by five methods (steel-frame house)

**Temperature difference = temperature of other method – temperature of equivalent wall method*

According to the results, in case that the programs for deriving "equivalent wall" properties are not available, the combined-property method seems to be the first choice to be used to model the energy performance of the wood-frame and steel-frame house. Since it would take longer to understand the "equivalent wall" method and to develop the program to integrate the thermal properties of the assemblies. The third method (W/WO stud) seems to be the second best choice because the results are still close to those of the equivalent wall and it does not require the R-value calculated from the two-dimensional heat transfer program as in the combined-property method. However, longer time is needed for the data input and simulation which might not be suitable for a large number of simulation run for the sensitivity analysis which is a part of our further studies.

For the first method (without stud), although the differences of the results are less than 2%, it can not be used for our further studies because it cannot differentiate the energy consumption of the wood-frame and steel-frame houses. The last method, only R-value, should not be used since the figures exceed the acceptable range.

For further study on the energy performance of the wood-frame and steel-frame houses, the method that we decided to use is the "equivalent walls." There are two main reasons. First, the programs for deriving the equivalent wall are already available and developed; therefore, the time spent on deriving the thermal properties of the frame wall, with the combined-property method and the equivalent wall is slightly different (about fifteen minutes more for the equivalent wall method). Second, theoretically, the equivalent wall should provide more accurate results, thus, it would be the preferred choice.

ECONOMICAL EVALUATION

The objectives of the study are to compare the energy performance of the steel-frame house and the wood-frame house with the conventional concrete-frame house, and to evaluate the economical value of the houses based on their construction costs and electricity costs.

The energy consumption for the cooling, lighting, and electrical equipment of the concrete-frame, a wood-frame, and a steel-frame house were simulated by the EnergyPlus. The building components of all three construction types are shown in Table 1. The details of the exterior walls for each construction type are shown in Figure 8.

The construction costs of the three types of the houses were estimated based on the construction drawings and construction specifications. The total cost of the house includes the cost of architecture, structure, lighting, sanitary, construction operation, and tax.

The electricity cost was calculated based on the method used by the Metropolitan Electricity Authority. The total electricity cost includes the service charge, fuel adjustment charge (Ft), and tax. The coefficient of performance (COP) of the air conditioner was assumed to be 2.5. The economical indices are payback period (PB), net present value (NPV), and internal rate of return (IRR). The escalation rate of the electricity is 3% per year and the discount rate is 5%. The payback period which is over seven years will not be considered economical.

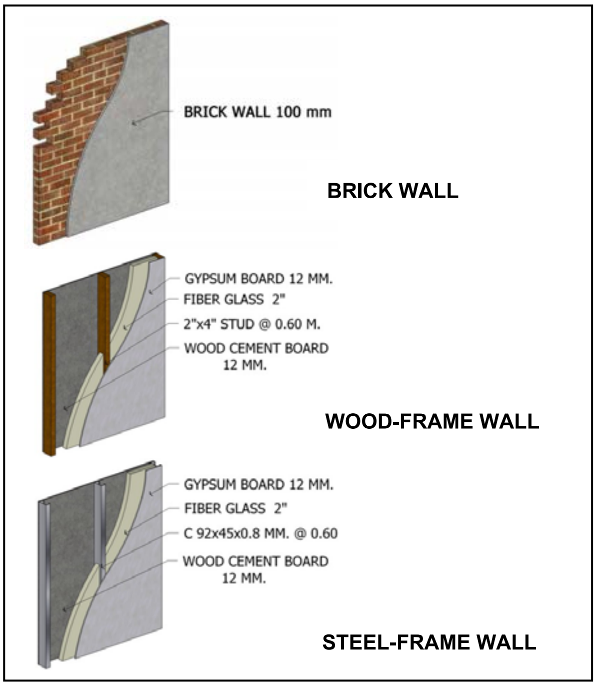

Figure 8. Exterior walls of concrete-frame, wood-frame, and steel-frame houses

DISCUSSION AND RESULTS ANALYSIS [2]

The construction costs of the concrete-frame house, wood-frame house, and steel-frame house are 66,226, 81,227, and 73,244 USD respectively. The costs of the wood-frame house and steel-frame house are 23% and 11% higher than the cost of the concrete-frame house respectively. An annual energy consumption of the wood-frame house and steel-frame house are 7.0% and 8.8% lower than that of the concrete-frame house respectively. The wood-frame and steel-frame house can save 107 and 134 USD per year on the electricity costs respectively (Table 4, Figure 9).

Table 4. Construction cost, electricity use, electricity cost, and payback period of concrete-frame, wood-frame, and steel-frame houses

METHOD	CON - CRETE	WOOD FRAME	STEEL FRAME
1. Construction cost (USD*)	66,226	81,227	73,244
2. Electricity Use (kWh / year)	15,305	14,237	13,961
3. Electricity cost (USD/ year)	1,466	1,359	1,332
4. Elec. Savings (USD/ year)	-	107	134
5. Payback period (years)	-	141	52

* based on currency exchange (1 USD = 38 THB)

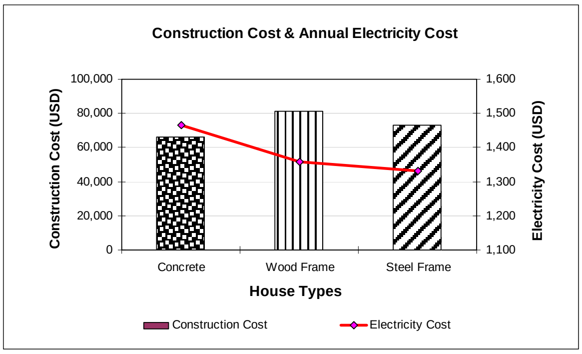

Figure 9. Construction cost and electricity cost of three types of houses

The payback periods of the wood-frame and steel-frame houses are longer than 30 years due to the high construction cost and small electricity cost savings compared with the concrete-frame house. Since the payback periods are much longer than the preferred payback period, other economical indices, NPV and IRR, are not considered. Based on the construction cost and electricity cost, the steel-frame house is more economical than the wood-frame house. However, the economical value of the steel-frame house is not attractive enough to replace the conventional concrete-frame house.

The reason why the steel-frame house in this study can save more energy than the wood-frame house can be explained as follows. The exterior walls of the wood-frame house have higher R-value than that of the steel-frame house. During daytime, the inside face temperature of the exterior walls of the wood-frame house is lower than that of the steel-frame house. However, during night-time when air conditioners are used, (zone air temperature is 25 ^{o}C), the inside face temperature of the exterior walls of the wood-frame house are higher than that of the steel-frame house (Figure 10). This higher inside face temperature of the wood-frame walls results in higher cooling loads, compared to that of the steel-frame house.

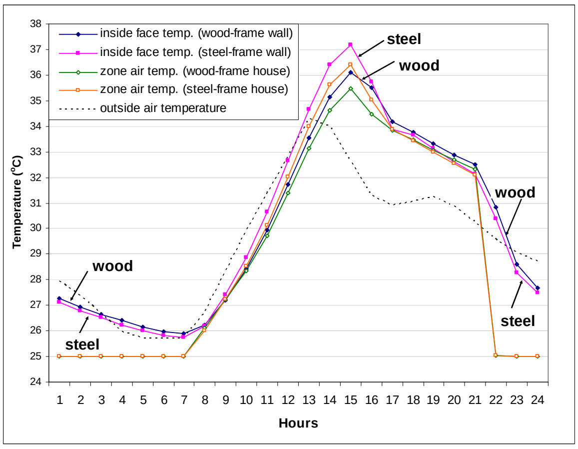

Figure 10. Inside surface temperature of the wood-frame and steel- frame walls and air temperature of the bedroom zone of both types of the houses

To further investigate whether the exterior walls with higher R-value increase the energy consumption of the wood-frame and steel-frame houses, three types of exterior walls were then simulated. The first one was the original exterior walls (Figure 9), the second one had no insulation in stud cavity, and the third one had additional 1-inch PU foam sheathing. Figure 11 shows that the wood-frame and the steel-frame house whose exterior walls have higher R-value consume more energy than the house whose exterior walls have lower R-value. In addition, by using the second wall types (no cavity insulation), the cost of the houses and the electricity cost are reduced, therefore, the payback period of the houses are shorter than that of the original one but it is still longer than 30 years.

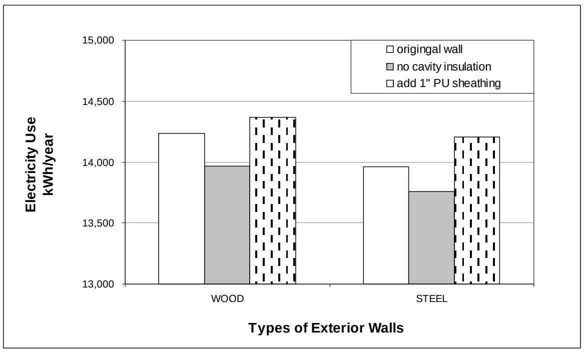

Figure 11. Energy consumption of wood- frame and steel- frame house with different exterior walls

CONCLUSIONS

We have compared the cooling loads calculated by different methods for the wood-frame and steel-frame houses in EnergyPlus. The results show that the difference of the cooling load of the three methods (without stud, w/wo stud, and combined-property methods) is less than 2% compared with the equivalent wall method. The results of this study are based on the Bangkok weather data, therefore, with different weather data and house types, it needs further study. The wood-frame house and the steel-frame house consume less energy than the concrete-frame house. The annual energy saving of wood-frame and steel-wood frame houses are rather small (wood 7.0% and steel 8.8%) compared to the additional costs (wood 23%, steel 11%) of the concrete-frame house. The payback periods are longer than 30 years for both house types. The energy consumption of only clear walls of the wood-frame and steel-frame house presented in this paper was modeled. The energy performance concerning the whole walls (including interface details) needs to be further explored. In addition, more factors for evaluating the economical values of the wood-frame and steel-frame house, such as construction times, needed to be explored.

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