2018 Modular and Offsite Construction (MOC) Summit
@
World of Modular, March 22-25
The Diplomat Beach Resort, Hollywood, FL, USA

Towards net zero energy modular housing: a case study

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ABSTRACT

The paper summarizes an investigation of the performance of container based housing units developed by Ladacor Ltd, and compares this performance to traditional housing constructed according to existing standards and codes. The results indicate that the case study housing system can reduce thermal loads (heating and cooling) by about 57% as compared to the same house designed according to the code. Implementing additional efficiency measures and solar design strategies such as increased south window size, suitable shading devices, thermal mass, and more airtight construction, leads to improved performance. This enhanced scenario can reduce the thermal load by 72% as compared to the code scenario and by about 35% as compared to the original case study system.

Achieving a net-zero energy status can be reached by integrating photovoltaics on the south roof of the single-family housing designed with Ladacor roof, assuming energy efficient appliances, lighting and domestic hot water. The optimal case can reach a net positive energy status, with a PV system integrated on the south facing roof surface. Results from this investigation can serve in developing innovative design concepts and guidelines for the design of low cost, self-sufficient modular housing.

KEYWORDS

Shipping container, modular housing, energy modelling, energy efficiency, building envelope

INTRODUCTION

Employing prefabrication in the construction of houses offers a means for improved energy efficiency and reduced cost of these houses (e.g. Dumas et al. 2016; Ganiron 2016). In fact, studies carried by Canada Mortgage and Housing Corporation (CMHC 2016) indicate that prefabricated houses allow about 55% savings in cost, and 43% reduction in carbon dioxide (CO2) emissions over site-built houses.

Modular method of construction, as a form of prefabrication has several advantages such as: reduced construction time and landfill waste, improved indoor air quality through environmental friendly materials, better performing envelope, improved energy performance, and possibility for material recycle and reuse (Lim et al. 2013; Ganiron and Almarwae 2014). Amongst the most recent forms of modular housing gaining popularity in the construction industry is the application of shipping containers as building blocks. A number of research studies point to the potential of achieving affordable, energy efficient modular structures employing container-based structures (see for e.gs; Slawik, et al. 2010; Robinson et al. 2011; Bernardo et al. 2013; Lim et al. 2013; and Ganiron and Almarwae 2014). The main focus of existing research is on ways to improve the thermal performance of container-based structures (Pena and Kurt 2012; Alemdag and Aydin 2015). Nevertheless, research on the utilization of container envelope in the construction of energy efficient buildings is still at its early stage in North America.

The first stage in improving the energy efficiency of the container box is to devise an energy efficient building envelope (Thun and Velikov 2013). Specific envelope design requirements for improved energy efficiency include: high performance windows, airtight construction, high performance thermal insulation, and proper shading devices to control solar heat gain. In lightweight structures, additional strategies are required, such as incorporating phase change materials (PCMs) to improve thermal capacity (Zhou et al. 2012; Xiao et al. 2013).

The study presented in this paper is part of a project developed in collaboration with Ladacor ltd, a Canadian modular construction industry. It investigates the performance of container-based structure for residential buildings, and determines its potential to achieve net-zero energy status in Calgary (AB, Canada). The paper summarizes the investigation of the performance of container based housing units and compares this performance to traditional housing constructed according to Canadian National codes. Results from this investigation can serve in developing innovative design concepts and guidelines for the design of low cost, self-sufficient modular housing.

METHODOLOGY

The investigated housing unit is a 5-bedroom duplex design provided by Ladacor Ltd. This is a single-story building with a basement floor (see Figure 1 below). The basement floor plan design follows conventional building envelope design specifications in Canada. The containers are not utilized in the basement and foundation wall construction. The main floor design combines four 12.2 m long container boxes to make a single-family unit. This study adopts a reused Intermodal Steel Building Unit (ISBU) designed with shipping container shell to the International Organization for Standardization (ISO).The total house dimension is thus 12.2 m in length, 9.75 m in width, and 2.9 m in height. Two container boxes are joined horizontally to make a module, and each module is fabricated together at the factory removing one side of the longer exterior wall (see, Fig. 1). The adjoining wall between two container modules (marked as “Marriage wall” in Figure 1) has the same construction and insulating qualities as the exterior walls (as designed by Ladacor).

The first stage of this research consists of designing two reference case models termed hereunder *Code case* and *Ladacor case*. The code case building envelope characteristics are developed in compliance with Alberta Building Code (2014) standards, the National Building Code of Canada (2015), recommended for low-rise housing and small buildings in Canada, and the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) standard for dwellings (ASHRAE 60.1). For the Ladacor model, the building envelope characteristics are based on specifications and drawing details provided by the company. These reference cases are to serve as benchmarks for the comparative analysis of the energy performance. Table 1 summarizes the characteristics of these two cases.

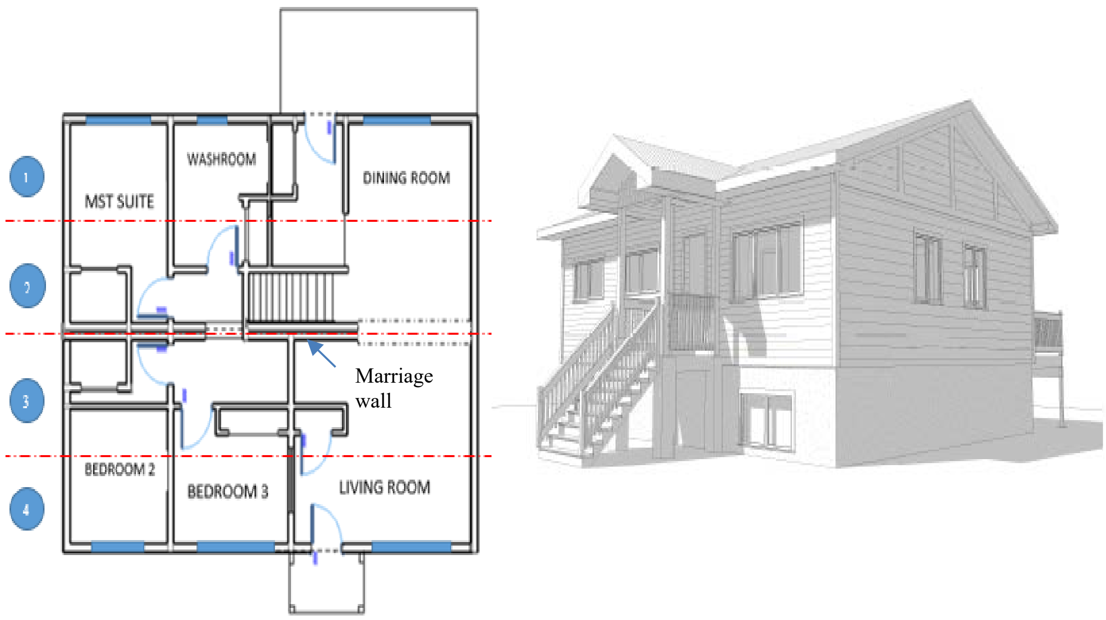

Figure 1. Plan and three-dimensional perspective of 5-bedroom container duplex. Source: Ladacor Advanced Modular Systems 2017.

In the second stage, extensive simulations are conducted employing EnergyPlus in conjunction with Google SketchUp Pluggin to assess the impact of various building envelope components. These include insulation of opaque area, infiltration rate, window assemblies, thermal mass, window size, solar shading controls, phase change material and building orientation, on the overall energy consumption. Results of these simulations are compared to the Ladacor reference model. Potential electricity generation from PV integrated in the roof is then estimated to determine the potential of achieving net zero energy status.

In addition to the building envelope characteristics discussed above, a few assumptions are adopted in the EnergyPlus model. Lighting, people and equipment schedules are set to suit weekly and daily activities. For this study, the infiltration rate of 0.5 ACH (@75 pa) is adopted for the code case based on ASHRAE's recommendation of Average Air tightness (Fennell and Haehnel 2005) while Ladacor case assumes more tight construction of 0.1ACH (@75pa). Actual tests to verify the air-tightness of the structures are recommended.

The domestic hot water system is estimated to be 1817 KWh/year, based on efficient hot water use, and assuming a consumption of 2.62KWh/occupant/day (Sartori et al. 2010). This is based on the assumption of hot water usage of 50 L/day/person. This value is derived from information provided in the literature (e.g. i IEA task 26, EN 15316) and the Canadian EQuilibrium Initiative), with the assumption that it is possible to reduce significantly the daily hot water (DHW) consumption, using different methods (e.g., use of low-flow showerheads). The interior lighting power density is calculated as 5.0 W/m^2 high efficiency LEDs for dwelling units provided by the National Energy Code of Canada for Buildings (Natural Research Council of Canada 2015b).

Table 1. Code, Ladacor and Optimal Case Building Characteristics

Building Envelope Characteristics	Reference Cases		Improved Case
	Code Case	Ladacor Case	Optimal Case
Total Building Area	237.83 m^2	237.83 m^2	237.83 m^2
Container floor Area	118.92 m^2 per floor	118.92 m^2 per floor	118.92 m^2 per floor
Building Dimensions	Length x Width x Height (12.2 m x 9.75 m x 2.9 m)	Length x Width x Height (12.2 m x 9.75 m x 2.9 m)	Length x Width x Height (12.2 m x 9.75 m x 2.9 m)
Building Envelope: Container Floor (K. m^2/W)	Container Wall: RSI 3.76 Roof: RSI 3.78 Boundary Floor: RSI 3.88	Container Wall: RSI 5.0 Roof: RSI 9.14 Boundary Floor: RSI 4.86	Container Wall: RSI 5.0 Roof: RSI 9.14 Boundary Floor: RSI 1.0 (without insulation)
Building Envelope: Basement Floor RSI (K. m^2/W)	Basement Wall: RSI 4.75 Basement Floor: RSI 3.54	Basement Wall: RSI 4.75 Basement Floor: RSI 3.54	Basement Wall: RSI 4.75 Basement Floor: RSI 3.54
Door	RSI 2.62	RSI 2.62	
Window Assembly	Low-e, double paned glazing (U-Value 2.0 W/ m^2K)	Low-e, triple paned glazing, argon filled (U-Value 1.2 W/m^2K)	Low-e, triple paned glazing, argon filled (high SHGC)
Air infiltration rate	0.5ACH	0.5 ACH	0.04ACH
Above Ground Window-Wall Ratio [%]	Total Façade Glazing: 6.4%	Total Façade Glazing: 6.4%	Total Façade Glazing: 10%
	South Façade: 13%	South Façade: 13%	South Façade: 40%
	East Façade: 4.4%	East Façade: 4.4%	East Façade: 4.4%
	West Façade: 0%	West Façade: 0%	West Façade: 0%
	North Façade: 7.5%	North Façade: 7.5%	North Façade: 7.5%
Envelope improvements	NA	NA	See summary of envelope improvements in results discussion below

RESULTS

The parameters studied include insulation level, airtightness, thermal mass, window area and orientation, glazing characteristics and shading devices. These parameters are systematically optimized, employing EnergyPlus and their effect on the energy performance are compared to code reference case. A summary of these results is presented below, both for the reference cases and the optimal case.

Reference cases

Figure 2 presents heating and cooling load for the living area and the basement, of each of the two reference cases (i.e., Ladacor and Code). The results show that the thermal loads of Ladacor model are 57% less than those of the code scenario. This is due mostly to better-insulated envelope combined with a more airtight construction. The study shows that, increasing the insulation value in the container floor construction leads to an increase in total building thermal loads. In fact, the building performs more efficiently with the reduction of insulation between the two floors by a factor of 4, thereby allowing for greater heat transfer.

Overall, the results demonstrate that the total building thermal loads are dominated by heating loads.

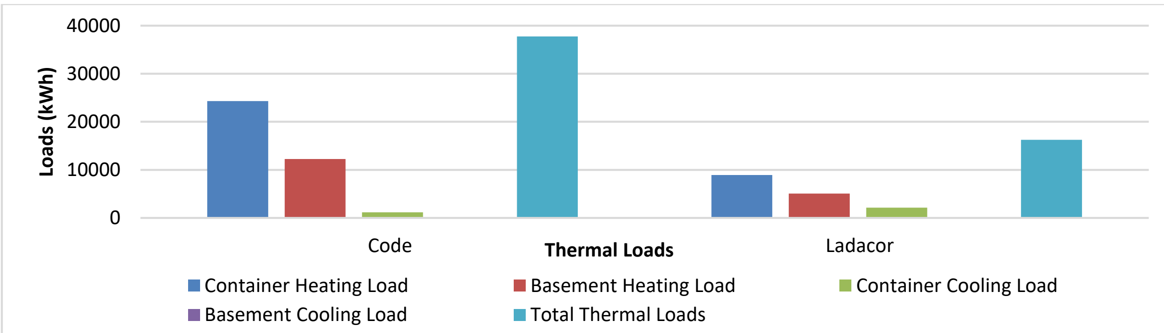

Figure 2. Comparison of reference cases

Envelope Improvements

The investigation of various design parameters indicates that a number of building envelope upgrades can be implemented to increase the energy efficiency over and above the performance of the Ladacor base case. These improvements include the following:

- Increasing solar heat gain coefficient (SHGC) of the triple pane window assembly.
- Reduction of thermal insulation in the container floor slab construction, by factor of 4.
- Adding 100 mm to the container floor slab as thermal mass.
- Assuming increased air-tight construction of 0.6ACH (@50Pa, to conform to passive house design).
- Increasing wall to window ratio of the south facade from 13% to 40%, to increase the passive solar heat gain potential.
- Adding interior solar blind to windows on all façade as shading control.
- Implementing overhangs on south facing windows to provide additional control of solar radiation.
- Introducing phase change material in the container envelope construction, to increase the thermal mass of the housing unit.

Implementing these upgrades to Ladacor case, results in reducing thermal load by about 72% as compared to the code case, and 35% as compared to Ladacor case. These results are presented in Figure 3 below.

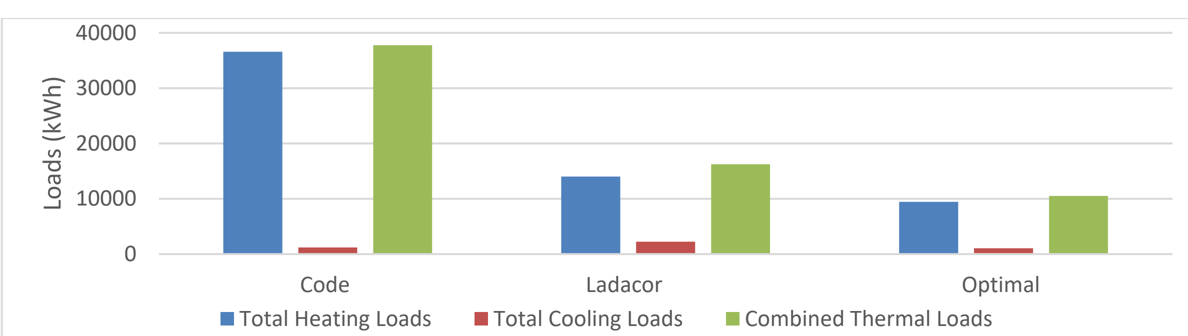

Figure 3. Comparison of thermal loads of envelope scenarios

Assuming that heating and cooling can be delivered to the housing units employing an air source heat pump of COP of 3.3 (that corresponds to commonly found heat pumps), the energy consumed for heating and cooling for the 3 scenarios (code, Ladacor, and optimal) are presented in Figure 4.

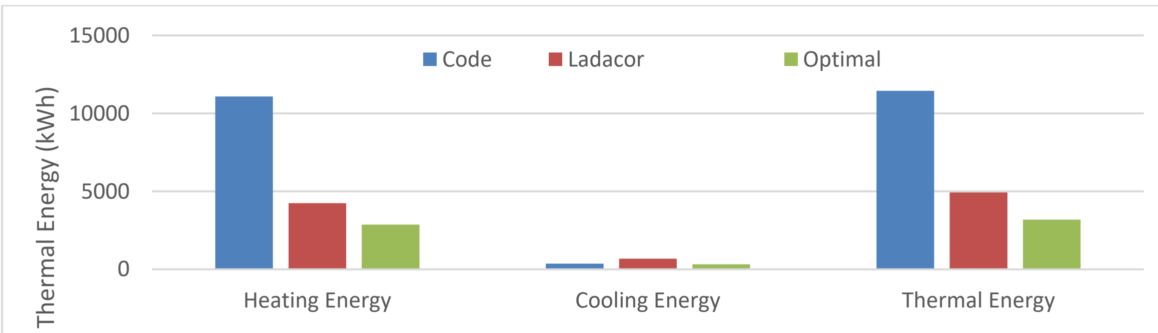

Figure 4. Comparison of energy performance of envelope scenarios

Building Integrated Photovoltaics (BIPV) and Net-Zero Energy Status

A PV system is assumed to be integrated on the total south facing surface of the Ladacor case roof, with the original inclination of the roof (i.e. 22^0). For the optimal case, two scenarios of PV tilt angle are analyzed, 30° and 45°.

The analysis shows that Ladacor and the two scenarios of the optimal case can achieve net zero energy and even energy positive status. The integrated photovoltaic system generates enough electricity to satisfy the building's energy demands for heating, cooling, lighting, electrical appliances, and domestic hot water system. A surplus or net-energy consumption of 5,836 kWh of electricity per annum is expected with the optimal case designed with 45° gable roof angle. The results are presented in Figure 5 below.

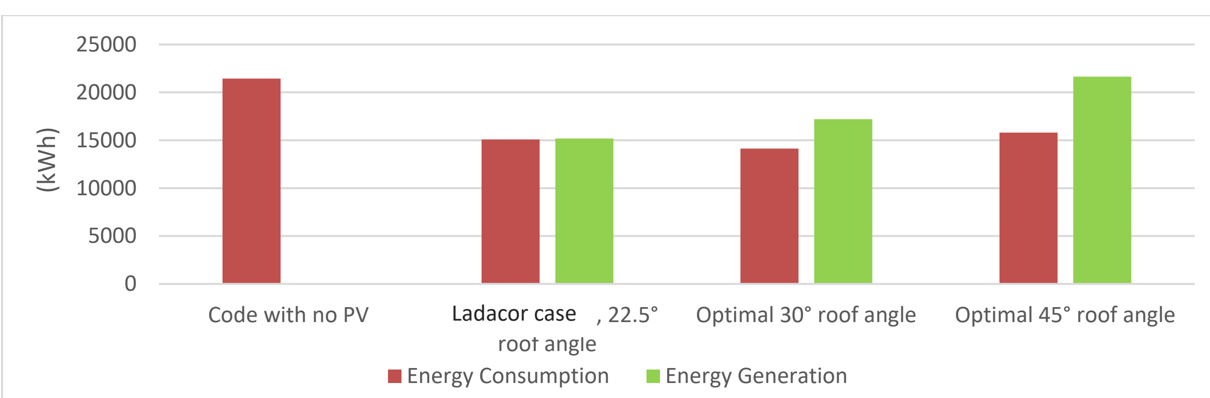

Figure 5. Comparison of net-zero energy status

CONCLUSION

This study investigates the performance of the container based housing system developed by Ladacor Ltd, and compares this performance to a commonly built housing unit, designed according to codes and standards. In addition, various design parameters are investigated to determine design strategies that can increase the energy performance of the studied, container based, single-family housing unit. These parameters are systematically optimized and their effect on the energy performance are compared to code reference case.

The results indicate that Ladacor housing system can reduce thermal loads (heating and cooling) by about 57% as compared to the same house designed according to the code. Ladacor case assumes an air-tight construction. This assumption is considered due to the continuous nature of the container envelope, which reduces possible leakage in the interface between various surfaces (e.g. walls, ceiling and wall, etc). Future tests to verify the actual air-tightness of the structures are however recommended, as air-tightness plays an important role in the performance of these housing units.

Implementing additional efficiency measures and solar design strategies such as increased south window size, appropriate shading devices, thermal mass, and more air-tight construction, lead to improved performance. This enhanced scenario can reduce the thermal load by 72% as compared to the code scenario and about 35% as compared to Ladacor system.

Achieving a net-zero energy status can be reached by integrating photovoltaics on the south roof of the single-family housing unit designed with Ladacor roof, assuming energy efficient appliances, lighting and DHW. The optimal case can reach a net positive energy status, with a PV system integrated at 30° or 45° tilt angles.

This study demonstrates that incorporating passive solar design strategies such as optimal insulation levels, thermal mass, and glazing types and sizes, as well as south building orientation can significantly improve the energy performance of such housing systems. This study opens future research areas in life cycle analysis and life cycle costing of container-based units. Understanding the potential environmental impact, in terms of cumulative energy demands (CED), and (GHG) emissions will further indicate the whole life cycle benefit or constraints of container-based housing.

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