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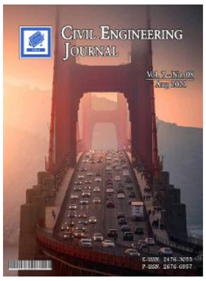

Structural and Thermal Performance Assessment of Shipping Container as Post-Disaster Housing in Tropical Climates

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Abstract

Shipping Containers (SC) are a viable option as temporary or permanent housing for disaster victims due to their modularity, strength, and availability in large quantities around the world. While SCs as alternative housing has been extensively explored, few studies have focused on the structural and thermal performance of SCs in a tropical monsoon climate. This paper aims to contribute to a better knowledge of SC building construction by (1) investigating the SCs structural performance when subjected to a variety of loads, including gravity, earthquake, and very strong typhoon, and (2) assessing the thermal performance in a hot and humid climate. The case of Leyte, Philippines, a hot, humid, and typhoon-frequented region, is considered in this study. To meet the objectives, two SCs were combined to build a single-family house. First, the structural strength of the SCs, including the effect of cuts and openings, were investigated using finite element analysis. Second, the thermal condition of the SC was compared using four models with different insulation materials: no insulation, PE foam insulation (R-12), slightly higher insulation (R-13 fiberglass batt), and very high insulation (R-49 fiberglass batt) through building energy simulation. The paper concludes that SCs have inherently high strength and can withstand strong wind and earthquake. Stresses due to cuts and openings were minimized when the cuts/openings were placed far from the corner posts. On the other hand, increasing insulation R-value did not improve the indoor thermal condition of the SCs. More work needs to be done on making SCs thermally comfortable in hot and humid climates.

Keywords: Shipping Container; Post-disaster Housing; Structural Assessment; Thermal Assessment.

1. Introduction

The world is extremely vulnerable to climate change impacts. The increase in global temperature causes extreme weather patterns that increase the occurrence of stronger typhoons, sea-level rise, and elevated storm surges in coastal regions. In recent years, countries in Southeast Asia have experienced more extreme events that have turned into disasters [1]. The Philippines is one of the most at-risk countries from tropical cyclones [2] and other natural disasters such as earthquakes, landslides, tsunamis, and volcanic eruptions [3]. According to the Center for Excellence in Disaster Management & Humanitarian Assistance [3], at least 60% of the country's total land area is exposed to multiple hazards, and 74% of the population is vulnerable to their impacts.

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In 2013, Typhoon Haiyan, locally known as Typhoon Yolanda, one of the deadliest natural disasters to strike the Philippines, caused devastating damages to properties and took the lives of people living in the affected areas. According to the 2013 Final Report of the National Disaster Risk Reduction and Management Council (NDRRMC) [4], Typhoon Haiyan had a velocity of 235 km/h (65.3 m/s) near the center with a gust of 275 km/h (76.4 m/s) prior to landfall in Central Philippines. It triggered heavy rains that caused widespread flooding and landslides, particularly in East Samar and Leyte provinces. As a result, it affected 16 million people, caused 6,300 deaths, displaced 4.1 million people, and damaged or destroyed 1.1 million houses. Damage to properties amounted to 93 billion pesos (US 1.82 billion dollars).

In response to the lack of temporary housing as well as permanent housing for disaster victims of Typhoon Haiyan, bunkhouses were constructed by the Philippine government's Department of Public Works and Highways (DPWH). The bunkhouses were located in four severely affected sites, namely: Tacloban City; Palo, Leyte; Basey, and Marabut in Samar. A total of 248 bunkhouses were built where each bunkhouse was divided into 24 rooms to accommodate as many families as possible [5]. Each room has an area of 8.64 square meters. The Sphere Handbook, a widely recognized benchmark for humanitarian response, states that shelters for disaster survivors should provide a minimum of 3.5 sq. m living space per person [6]. An average Filipino family has approximately five members, and in order to comply with the standard, the rooms should have a total area of 17.5 sq. m. In order to comply with the standard, the design of bunkhouses was later on modified from the original specification of 24 rooms to 12 rooms, each measuring 17.28 sq. m. DPWH spent PhP 838,000 (US 16,318 dollars) for each bunkhouse made from corrugated sheets, plywood, and coco lumber [7].

Many bunkhouses provided to Typhoon Haiyan victims were later destroyed by the succeeding Typhoon Hagupit, locally known as Typhoon Ruby, with a velocity of 230 km/h (63.9 m/s) [8]. The destruction of the bunkhouses was due to the under specifications during construction [9]. Also, the bunkhouses were only meant as temporary and not permanent shelters. Hence, there is a need to provide comfortable temporary shelters constructed in a shorter time with a lower construction cost in which people affected by natural disasters can evacuate to, stay safe in, and transition to permanent homes in order to rebuild their lives. Nezafati et al. [10] conducted a study to determine the optimal temporary strategic location using an analytic hierarchy process (AHP) considering access roads, vulnerable areas, firefighting centers, populated areas, fault lines, and medical centers. The study showed that the "distance from fault line" criterion is the most influential factor among other variables. The use of shipping containers (SCs) is a viable option for temporary shelters. SCs, made of steel, are strong, durable, and safe. Each manufactured container undergoes a series of stringent tests on static load, dynamic load, stacking, and "weatherproofness" or water tightness [11]. SCs are also prefabricated, modular, and stackable. They are compatible with practically every transport system and are easily accessible. Moreover, SCs are available in large quantities around the world and are relatively cheap compared to current construction materials. These characteristics make SCs a good material for the construction of temporary shelters. As a matter of fact, modified SCs have been designed by architects and engineers worldwide as alternative housing, office space, shops, and classroom [12-15].

Several studies had investigated the viability of SCs as a shelter for post-disaster reconstruction. Zhang et al. [16] qualitatively examined the social considerations of temporary housing by focusing on case studies of temporary housing experiences following Hurricane Katrina in 2005, the Black Saturday bushfire in Victoria, Australia in 2009, and the 2011 Christchurch Earthquake in New Zealand. Key social factors found to be significant to the success of SC temporary housing projects relate to flexibility in ownership, reuse, and sitting arrangement, and robust pre-disaster planning by authorities taking into account the varying characteristics of different types of disasters. Obia (2020) examined different architectural modifications of SCs (i.e., adding a roof, cutting openings on a wall, jointing units among others) for housing purposes of internally displaced persons [17]. Based on a social survey approach, results show that architectural modifications on the SCs are acceptable for accommodation purposes. In 2014, a checklist for container shelter was prepared based on Transitional Shelter Standard [18]. From the checklist, SCs fulfilled the requirements with regards to buildability, usable area, ventilation, color, and environmental toxicity. However, it does not meet the "weight and package" requirements due to its huge size and heavy weight compared to normal shelters.

While SCs seem to be a sustainable solution for housing purposes, concerns have been raised regarding their suitability with regards to structural stability and habitability. The Philippines is prone to strong typhoons, and the SC's structural performance, if it can withstand strong wind speeds during strong typhoons, is not yet established [13]. The group of Bernardo [19] investigated the structural integrity of SCs as single-family dwellings through finite element analysis considering dead load, live load, snow load, and earthquake load. While SCs are feasible as building systems, technical evaluation is not easy as structural elements comprising it are made up of noncommercial steel sections. Giriunas et al. (2012) examined how the modified and unmodified SC respond under gravity and lateral loading based on finite element analysis [20]. Their study demonstrated the effectiveness of the SC's walls and roof to resist the loads. In 2018, Tan & Ling provided a comprehensive literature review on the technical suitability of SCs as shelter, which includes buildability, structural performance, and constructability [15]. Their study concluded that SCs have inherently high strength for obtaining shipping container accreditation from ISO and have the unique advantage of multi-story constructability. SCs have the strength to resist the impact of floodwater and wind, but more work needs to be done for the adaptability of container housing in a tropical climate country, especially in construction detailing, cost, and structural reliability.

A significant problem in using SCs as housing is the heat since steel has a high thermal conductivity. Moreover, steel is also susceptible to condensation due to moisture. The Philippines has a tropical monsoon climate characterized by relatively high temperature, high relative humidity, and abundant rainfall [21]. The warmest month occurs in May with a mean temperature of 28.3°C and mean monthly relatively humidity varying between 71% in March and 85% in September [22]. For an environment of high temperature and high humidity, SCs require thermal insulation and a ventilation system to ensure a comfortable indoor environment [23]. Different types of thermal insulation can be employed depending on the availability of materials and resources. The R-value is the resistance to heat flow, where the higher the value, the greater the resistance to heat flow. The R-value depends significantly on the type of material, the thickness of the material, and density [24]. Each material can also be layered upon one another in order to increase the insulation. In this case, the R-values are simply added together.

De Asis (2010) surveyed thermal insulations applied to existing SC apartments and office spaces in the Philippines. Among the insulations used include Supertherm (R-19), which is a water-borne combination of high-performance aliphatic urethanes, elastomeric acrylics, and resin additives; double walls with fiberglass insulation; and double walls with foam insulation (R-value of 11 and higher) [13]. In 2017, Elrayies assessed the thermal performance of SCs in the hot and humid climate of Port Said, Egypt, by conducting comparative simulation studies of a conventional building, an uninsulated SC, and four externally insulated SCs with different insulation materials: rock wool, wool, closed-cell spray polyurethane foam (ccSPF) (R-15.75), and straw [25]. Results show that thermal insulation is irreplaceable in SCs as habitable spaces and that ccSPF is the most compatible thermal insulation followed by straw. Jamaludin et al. (2021) explored the potential of using untreated bamboo as insulation material for residential SCs under the hot and humid Malaysian climate [26]. Results show that the use of bamboo as insulation did not improve but further increased the indoor thermal temperature and relative humidity of the SC. Their study concluded that the SC as a building material for liveable space is not compatible with the hot and humid conditions of the equatorial climate. Shen et al. (2020) proposed climate-adaptive strategies in using SCs under cold, temperate, and hot-humid climatic zones [27]. For hot-humid climates, they recommended: the use of high-performance windows facing prevailing wind direction that must be well-shaded by both overhang and operable shutters; painting the roof and façade with light color for the purpose of more heat reflection during summer time; that buildings should be oriented in the direction perpendicular to the direction of the prevailing wind during summer months; and to install vertical vegetation for shading function at the East and West façade.

This study aims to contribute to a better knowledge of SC building construction by (1) investigating the SCs structural performance when subjected to a variety of loads, including gravity, earthquake, and very strong typhoon, and (2) assessing the SCs thermal performance in a hot and humid climate to augment the limited studies on this topic [23, 25-27].

2. Research Methodology

In this study, the viability of SCs as a shelter was evaluated by performing structural and thermal performance assessments. Figure 1 outline the steps of the assessment.

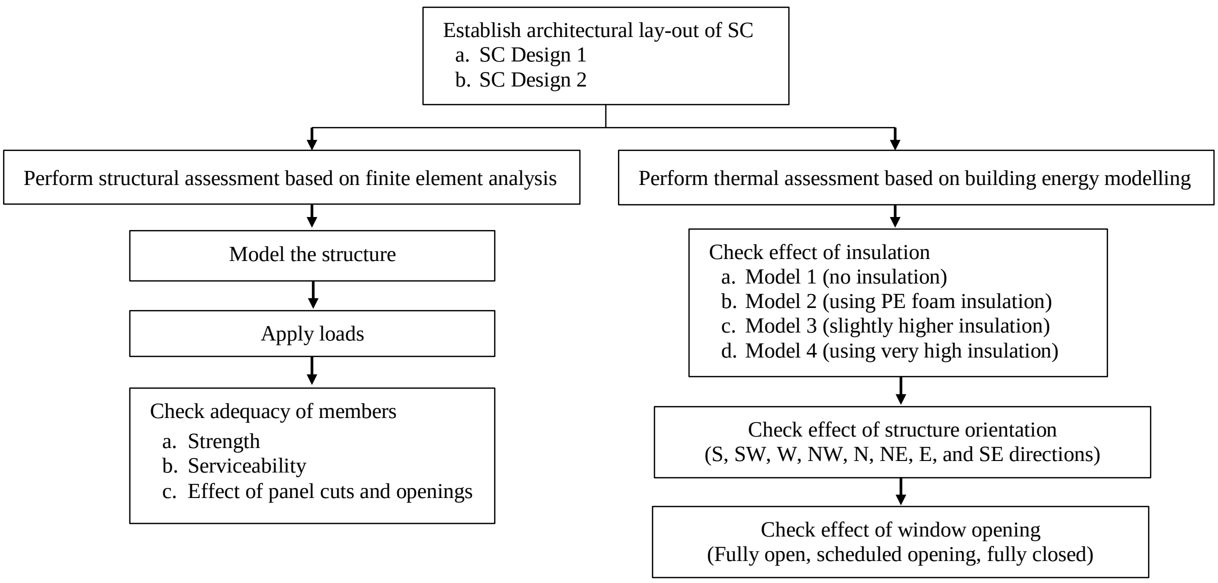


Figure 1. Framework of the research methodology

First, the architectural layout of the SC was established, as discussed in Section 2.2. Two SCs were combined in two layouts: a) SC Design 1 (side by side) and b) SC Design 2 (stacked together) to investigate which configuration would satisfy strength and thermal comfort criteria while satisfying shelter criteria on area and height. Second, the SC's structural performance was investigated by performing finite element analysis. Section 2.3 details the assumed material properties, structural model, loads, and adequacy check on strength, serviceability, and effect of window and door openings to the overall stiffness and resistance to lateral loads.

Lastly, the SC's thermal performance was examined based on building energy simulation as detailed in Section 2.4. The effect of insulation was assessed considering four models: (1) an uninsulated SC, (2) use of double-sided polyethylene (PE) foam insulation with R-12, (3) use of slightly higher insulation with R-19 fiberglass batt on walls and R-13 fiberglass batt on the roof, and (4) use of very high insulation with R-21 fiberglass batt on walls and R-49 fiberglass batt on the roof. Secondary simulations were also conducted to determine whether structure orientation and window opening might contribute to thermal comfort in SC houses. The structure was oriented in the S, SW, W, NW, N, NE, E, and SE direction. Moreover, a fully open, with scheduled opening, and fully closed window setting were considered.

2.1. SC Specifications

Shipping containers available in the market come in many different sizes. Common dimensions used are 6, 9, 12 m length; 2.4, 2.55, 2.7 m in height; and 2.4 m in width [25, 28]. For housing purposes, the most commonly used SCs have a length of 6 or 12 m and a height of 2.7 m. Such SCs are known as a high cube (HC) with commercial name of 20'HC (6 m or 20 ft long) and 40'HC (12 m or 40 ft long) [19, 29]. Table 1 shows the dimensions and the weight of the HCs. The difference in external and internal dimensions is attributed to corrugations, typically 25 mm in width, at the sides and top to provide higher inertia and more rigidity [14]. The payload weight is the weight of cargo the containers can hold. The tare weight is the weight of the container itself without any contents inside. Finally, the rating weight is the weight of the container and the maximum weight of the contents it can hold.

Table 1. 20'HC and 40'HC Dimensions [30, 31]

Model	Length (m)		Width (m)		Height (m)		Weight (kg)		
	Ext.	Int.	Ext.	Int.	Ext.	Int.	Payload	Tare	Rating
20'HC	6.0	5.9	2.4	2.35	2.89	2.70	28,180	2,300	30,480
40'HC	12.2	12.0	2.4	2.35	2.89	2.70	26,640	3,840	30,480

Figure 2 shows the primary components of a typical 20' ISO SC [32]. It has a front endwall, rear endwall, two sidewalls, roof, and base structure. Cold-formed, corrugated metal sheets, with thickness varying from 1.6 to 2 mm, form the front endwall, sidewalls and the roof. The base structure is made up of 28 mm thick, 19-ply hardwood plywood supported by a steel grid formed of several cross members and two bottom side rails. The load-carrying element of the shipping container is a steel framework, consisting of two top side rails, two bottom side rails, front top and bottom end rail, door header, door sill, four corner posts, and cross members.

2.2. Architectural Layout of Housing

To adhere to the shelter and settlement standard of 21 sq. m. per household, two units of 20' HC steel dry cargo containers were combined, resulting in a total area of 24.70 sq. m. The combined units also replicate the unit size of conventional medium-rise housing in the Philippines, which would be able to shelter a family of 6-8 people [13]. The 20' HC's internal floor-to-ceiling height of 2.7 m satisfies the minimum ceiling height for buildings of 2.4 m [33] and 2.0 m to aid air circulation in warmer climates [6].

Architect and urban planner Felino Palafox recommended that shelters should have at least two bedrooms. This is related to gender sensitivity, to give dignity to the female members of the family [34]. Figure 3 shows the proposed architectural layout of the containers consisting of two bedrooms, living area, dining area, bathroom, and lavatory. Wooden plywood panels were considered for the wall division. Figure 3(a) shows two containers combined side by side, referred herein as SC Design 1, whereas Figure 3(b) shows containers stacked together to form a two-story shelter, referred herein as SC Design 2. The dimensions of the doors and windows are assumed as: main door – 0.90×2.10m, interior doors – 0.80×2.10m, big window – 2.40×1.2m, and small window – 0.60×0.60m.

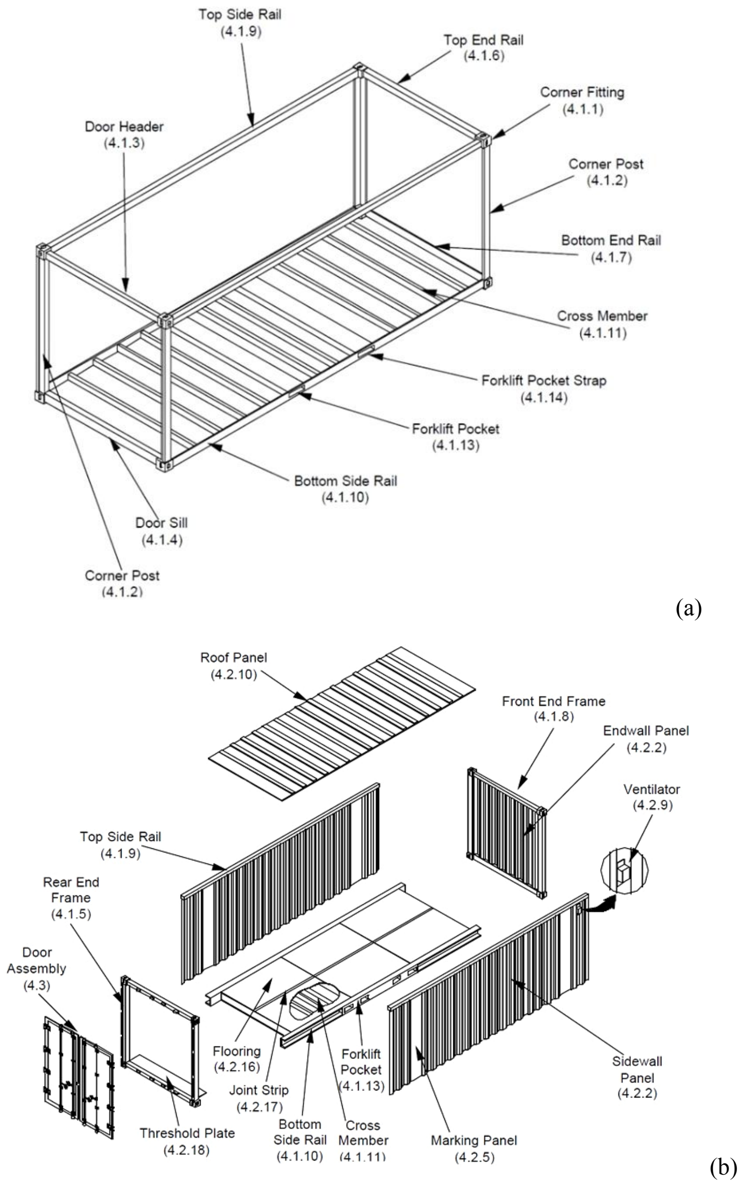


Figure 2. 20' ISO shipping container: (a) primary components and (b) exploded view [32]

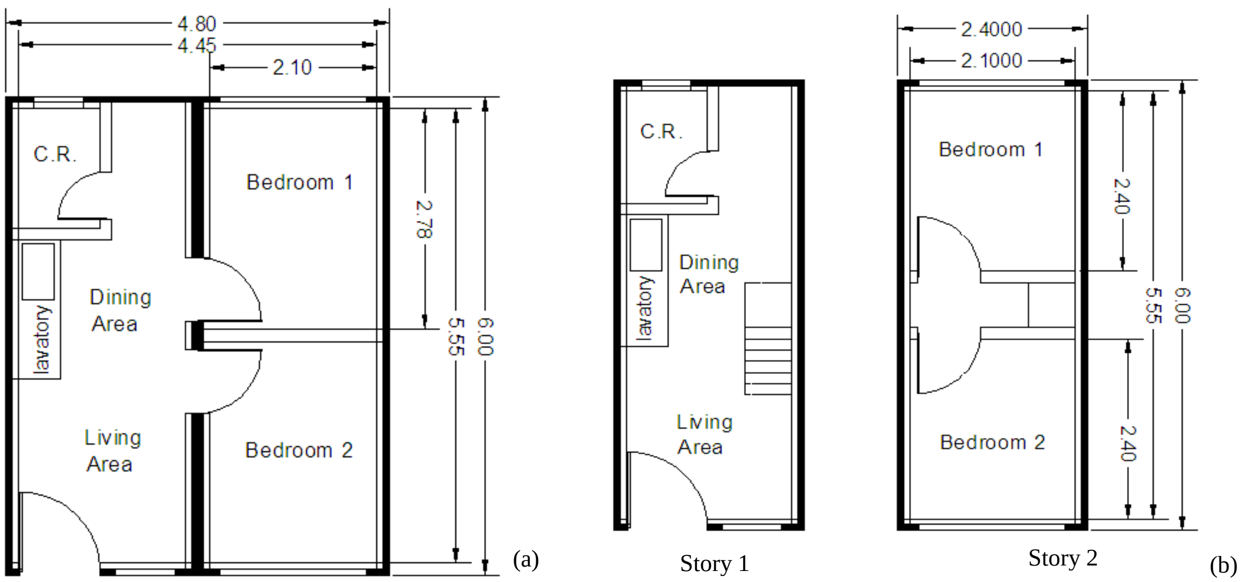


Figure 3. Architectural layout: (a) SC Design 1 and (b) SC Design 2

2.3. Structural Performance Assessment

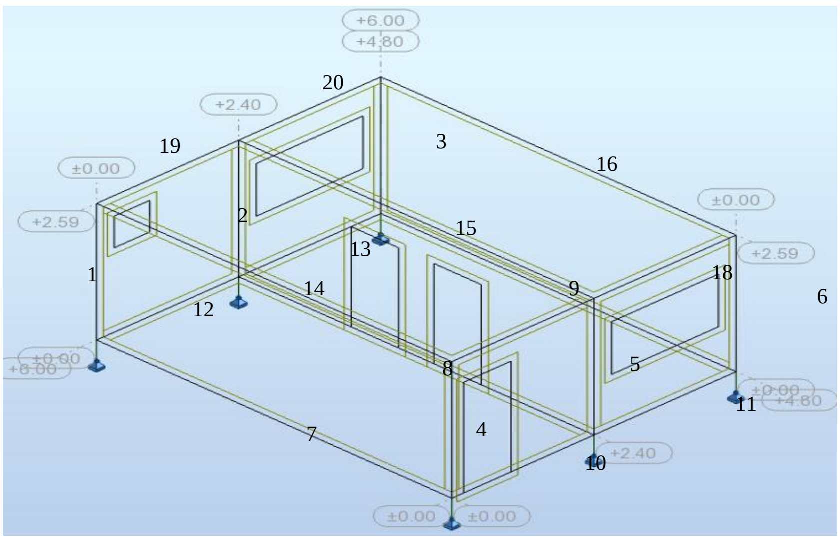
The structural performance of the SC shelter was assessed through finite element analysis using the Robot Structural Analysis Professional software of Autodesk. This software was selected for its wind load simulation, where velocities, pressure, and direction can be set such that simulation results are similar to wind tunnel testing. Wind tunnel tests are used to predict the wind loads and responses of a structure and structural components to a variety of wind conditions.

Figures 4(a) and 4(b) show the structural model of SC Design 1 and 2, respectively. The SC is made of anti-corrosive steel or Corten steel with yield stress (fyk) of 343 MPa, Young's modulus of 210 GPa, and Poisson's ratio of 0.30 [20]. For a 20' HC, the following section properties were assumed [30]: a) top side rails, front top end rail, door header - HSS 60×60×3mm; b) bottom side rails, end rail, door sill – 48×158×30×4.5mm cold-formed C section; c) corner posts – hollow section built-up of four L75x75x6mm; and d) walls and roof – trapezoidal plate with 2.0 mm thickness taking into consideration the corrugations assumed as shown in Figure 5 based on [19]. The sections were inputted in the software and their geometrical properties were directly computed. Side rails were modeled as linear beam elements, corner posts as linear column elements, and walls and roof as trapezium plate elements. The SC was assumed to be pinned-supported (all translations restrained) by footings at the four corners. While this study used simple modeling assumptions, Giriunas et al. (2012) has shown that five SC models of varying complexity and accuracy have comparable responses and that the simplest model captured the overall stiffness but over-predicts the load at first yield by 30% [20]. This study's model is similar to Giriunas et al. simplest model and was used as it is believed to provide a more conservative approach to using more complex models aiding in the technical evaluation of SCs in the field.

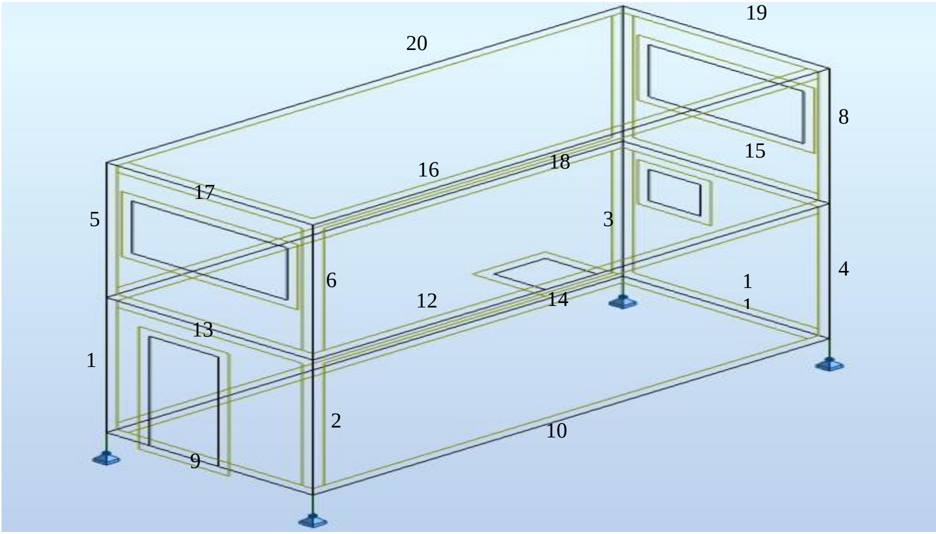
Based on the 2015 National Structural Code of the Philippines (NSCP), the following loads were assumed in the analysis: dead load of 77.3 kN/m^3 for the SC's self-weight, 1.0 kPa partition loads, 0.0028 kPa/mm fibreboard insulation on roof and walls; and live load of 1.9 kPa for residential occupancy [35]. For wind load calculations, the wind velocity pressure q_z in N/m^2 at any height z was computed as:

$$q_z = 0.613 K_z K_{zt} K_d V^2 \quad (1)$$

where K_z is the velocity pressure exposure coefficient, K_{zt} is the topographic factor, K_d is the wind directionality factor and V is the basic wind speed in m/s. K_z is determined using NSCP Table 207.B.3-1 and is a function of height and ground terrain. In this study, the assumed site is at Tacloban City, Leyte, the site of extreme typhoon damage during Typhoon Haiyan. Ground terrain assumed is Exposure C category which includes open terrain with obstructions, flat open country, grasslands, and all water surfaces in regions with records of extreme typhoons. K_d is assumed as 0.85 based on NSCP Table 207A.6-1. Wind speed V is 290 km/h (80.6 m/s) with the assumed site at Tacloban City, Leyte based on NSCP Figure 207A.5-1A.

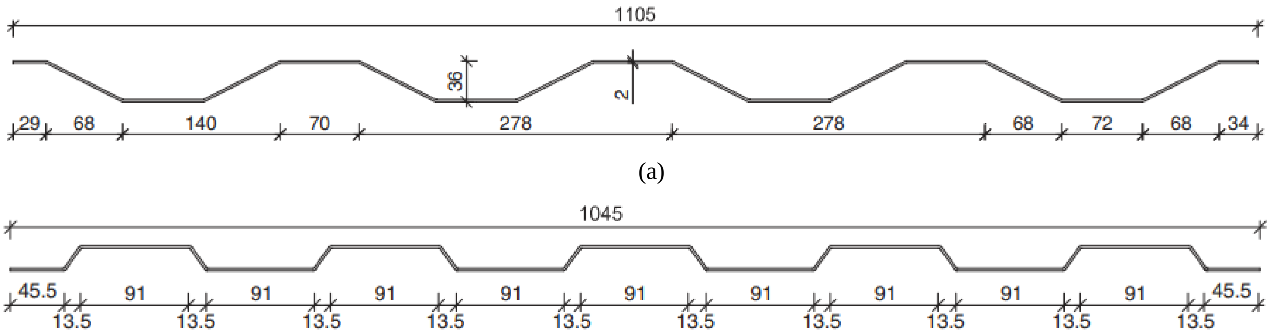


(a)



(b)

Figure 4. Structural model: (a) SC Design 1 and (b) SC Design 2



(a)

(b)

Figure 5. Corrugated plate: (a) sidewalls and (b) roof [19]

Earthquake loads were computed based on the Simplified Static Force Procedure since the SC housing is not more than two stories in height. It is computed as:

$$V_{shear} = 3C_a W/R \tag{2}$$

where V_{shear} is the total design lateral force or shear at the base, C_a is the seismic response coefficient for the soil profile type, W is the total weight of the structure, R is the numerical coefficient which represents the ductility capacity of the lateral force-resisting system. In this study, Tacloban City, Leyte is considered as Seismic Zone 4. Soil profile type S_D was assumed since, as per 2015 NSCP, this soil type can be assumed when soil properties are not known in sufficient detail. R of 3.0 was assumed for steel systems not specifically detailed for seismic resistance. C_a is then computed as:

$$C_a = 0.44N_a \tag{3}$$

where N_a is the near-source factor assumed as 1.2 as per NSCP Table 208-4. Dead load, live load, wind load, and earthquake load combinations using the Load and Resistance Factor Design for the ultimate limit state and the serviceability limit state were checked based on 2015 National Structural Code of the Philippines (NSCP) [35].

Limit state is a condition of a structure or member beyond which it becomes unfit for service and is judged to be no longer useful for its intended function (serviceability limit state) or to be unsafe (strength limit state) [35]. Strength limit state for axial force, shear force, and bending moment were checked. The adequacy of the beam and column elements was determined through the D/C ratio. Demand (D) is the computed response induced in a member by applied loads which can be expressed in terms of axial force, shear force, or bending moment. It is obtained from the results of the structural analysis. Capacity (C) is the actual strength of structural members calculated as per Chapter 5 of NSCP for the main structural members. D/C ratio must be less than or equal to one in order for a member to be adequate [35].

Serviceability is a state in which the function of a building, its appearance, maintainability, durability, and comfort of its occupants are preserved under normal usage [35]. Limiting maximum structural deflection shall be chosen with regard to the intended function of the structure. In this study, the maximum allowed deflection for the SC was based on ISO 1496 [11]. The effect of panel cuts and openings due to doors and windows in SCs was also determined by incorporating these in the model. It is important to note that any cutting and opening alterations done to the shipping container can cause a reduction in strength and stress build-up near its edges [20].

2.4. Thermal Performance Assessment

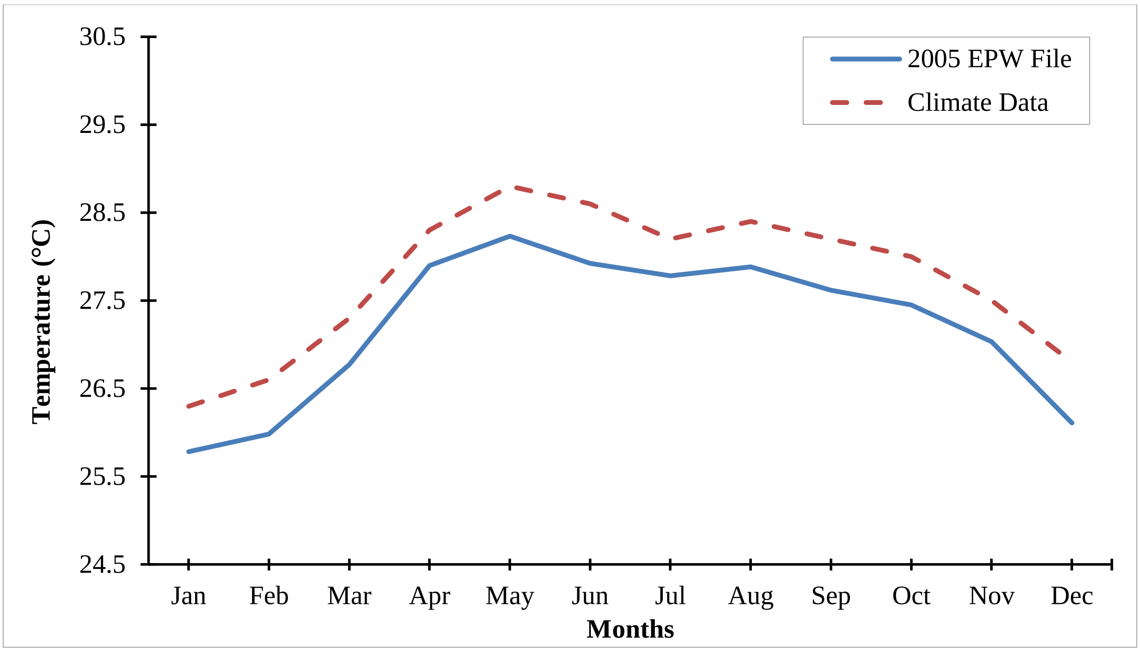
To assess the thermal performance of the SCs, building energy modeling (BEM) was conducted. BEM is a branch of building information modeling (BIM) that examines the energy use and indoor conditions of a structure. BIM is the use of virtual models and simulations to assist in the architectural design, engineering design, and management of buildings. In performing BEM, the parameters of interest are physical appearance, material properties, area use, and structure location.

Two models were created based on SC Design 1 and 2. The model creation was conducted using BEopt, with the aid of the EnergyPlus engine for simulation. BEopt is an open-source software for designing energy-efficient and low-cost residential buildings. A limitation of this software is that it does not account for the effect of indoor walls and partitions as it assumes all indoor walls do not transfer heat. In this study, the windows were assumed to have an area covering 30% of the front and back wall, to be made with metal frames, and to allow open air at all times. The doors were assumed to be swinging and to be made from 1.85 m^2 of wooden material. Wood was chosen as the material due to its availability and ease of use. To simulate the effect of nearby houses, it was assumed that similar SC neighbors, one on each side, were present. The site was assumed to be in a rural terrain of Tacloban City, Leyte.

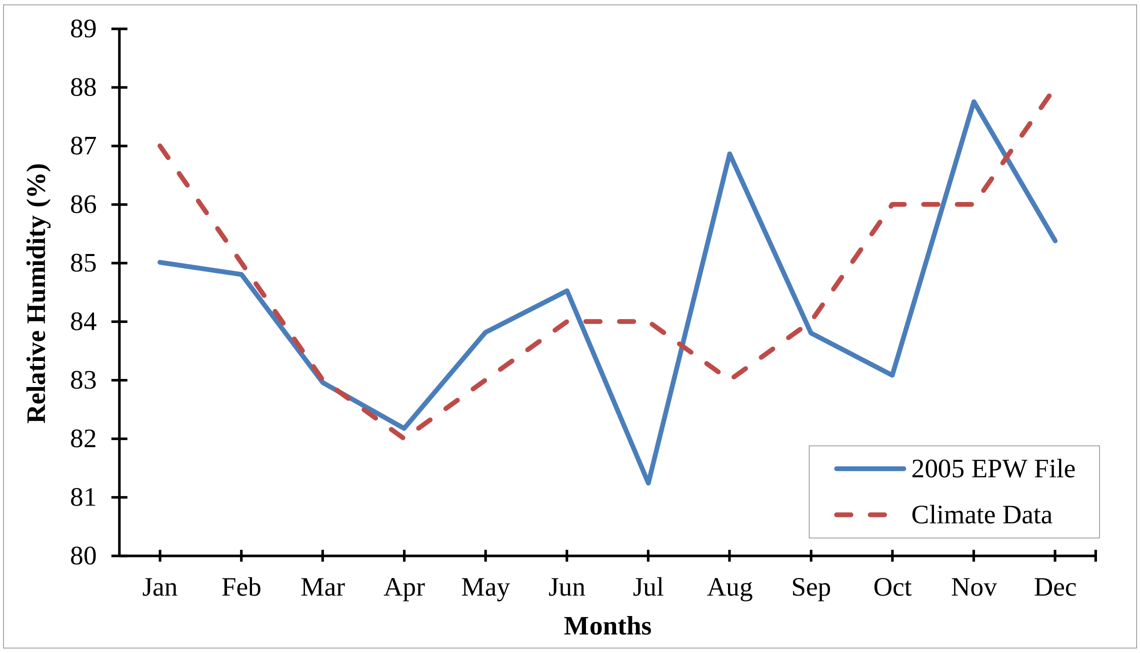
Thermal insulation controls surface temperature and reduces energy cost. It reduces the heat transfer between two objects of different temperatures, such as a building and the environment. In order for a material to be used as a thermal insulation, it must limit the heat convection, conduction, radiation, or a combination of the three [36]. The measure of a thermally insulating material's resistance to heat flow is referred to as the R-value. The R-value depends on the type of material, the thickness of the material, and the material's density [24]. Each material can also be layered upon one another in order to increase the insulation. In this case, the R-values are simply added together. The higher the R-value, the greater the effectiveness and the higher the resistance to heat flow [36].

In the study, four insulation models were considered to determine whether the use of a high R-value of insulation can result in a thermally comfortable shelter. These models incorporate no insulation, PE foam insulation, slightly higher insulation, and very high insulation. Model 1 is the uninsulated SC. Model 2 made use of double-sided PE foam insulation with aluminum coating having an R-value of 3. This insulation material is commonly used in the Philippines. In this model, four layers of 16 mm thick PE foam insulation were used on the walls and ceiling to obtain R-value of 12. Model 3 utilized slightly higher insulation through the use of R-19 fiberglass batt on 50 mm by 150 mm studs at 0.60 m spacing on the walls and R-13 fiberglass batt on 50 mm by 100 mm studs at 0.60 m spacing on the roof. Lastly, Model 4 utilized very high insulation through the use of R-21 fiberglass batt on 50 mm by 150 mm studs at 0.60 m spacing on the walls and R-49 fiberglass batt on 50 mm by 100 mm studs at 0.60 m spacing on the roof. In all four models, a layer of marine plywood with an R-value of 1.25 installed on its flooring was accounted for in the simulation. From the BEopt simulation, important outputs are the indoor temperature, indoor relative humidity, and wind speed at structure which are used in the thermal comfort analysis.

The simulation was run under the 2005 climate data of Tacloban City, Leyte, Philippines, taken on an hourly basis, in the form of EnergyPlus Weather Data (EPW) file representing the outdoor temperature, outdoor relative humidity, and wind/airspeed. Comparison between the mean monthly climate data used and climatological normal values can be seen in Figure 6 [37, 38]. Instead of the hourly analysis on the hottest and coldest day of the year, this study considered the mean monthly temperature and relative humidity to focus on the long-term thermal comfort of the SC within a year. Mean value is computed as the arithmetic average of the mean daily minimum and the mean daily maximum for the month in question.



(a)



(b)

Figure 6. Comparison between the 2005 EPW file [37] and the climatological normal values of Tacloban City, Leyte (1981-2010) [38]: a) mean temperature and b) mean relative humidity

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55-2017 "Thermal Environmental Conditions for Human Occupancy" was used as a basis for checking if the simulated results can achieve thermal comfort [39]. ASHRAE Standard 55 defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment." Thermal comfort is associated with climatic factors and personal factors. Climatic factors include air temperature, mean radiant temperature, relative humidity, and wind/airspeed. Air temperature is the average temperature, with respect to location and time, of the air surrounding an occupant. Mean radiant temperature is the uniform surface temperature of an enclosure where an occupant would exchange the same amount of heat as in the actual non-uniform space, calculated from the weighted temperature average of each surface divided by the total area of the space. Relative humidity is the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure. Wind/airspeed is rate of air movement at a given space in time regardless of direction. Personal factors include activity level (metabolic rate) and occupant clothing (degree of insulation). Metabolic rate is the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. Metabolic rate is accounted for as the personal activity of occupants and expressed in met units, where 1 met is a person at rest [39]. Clothing insulation represents the thermal insulation from clothing and is expressed in clo units. Winter clothing is equal to 1.0 clo while summer clothing is equal to 0.5 clo [39]. Thermal comfort is assessed based on indices Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). PMV is an index that predicts the mean value of votes of a group of occupants on a seven-point thermal sensation scale that is based on the balance of heat within the human body. PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied occupants (i.e., too warm or too cold). Thermal comfort can be obtained with a PMV of ±0.5 and PPD of at most 20% [39].

The indoor conditions were checked using the CBE Thermal Comfort tool, a free browser tool for checking thermal comfort compliance to ASHRAE 55 [40]. Based on air temperature, mean radiant temperature, and airspeed, the operative temperature is calculated. Operative temperature is a simplified measure of human thermal perception. In many spaces, with low air velocity and where air temperature and mean radiant temperature may be similar, air temperature alone can be a reasonable indicator of thermal comfort [41]. In this study, since the SC house is naturally ventilated and no additional heating is applied to the surface, the operative temperature is assumed equal to the indoor air temperature. Indoor air temperature, indoor relative humidity, and wind speed at the structure from the results of the BEopt simulation were used. Metabolic rate was assumed as 2.0 mets (or 116.4 W/m^2), equivalent to a walking speed of 0.9 m/s, which is relatively close to the average walking speed of 1.1 m/s [39]. This metabolic rate was chosen as it was judged to be the highest form of activity that can be done on average in the house. Clothing insulation was assumed to be 0.5 clo (or 0.0775 m^2-°C/W) which is the typical summer clothing. A value of 0.25 clo is also acceptable as it is the minimum clothing insulation and is associated with the use of undergarments, slippers, sleeveless or scoop-neck blouse, and shorts.

Secondary simulations were also conducted to determine whether structure orientation and window opening might contribute to thermal comfort in SC houses. The structure was oriented in the S, SW, W, NW, N, NE, E, and SE direction. Moreover, a fully open, with scheduled opening and fully closed window setting were considered as windows allow the increase and decrease of indoor relative humidity through occupancy-controlled natural ventilation. Windows can also prevent solar heat gain through glazings with low-E coating and conductive heat through insulated frames [42]. Hence, window insulation through the use of special triple-pane insulated windows, considered the most efficient among the glazed window types [43] but the most expensive, with R-value of 6 was considered.

3. Results and Discussion

3.1. Results of Structural Performance Assessment

ISO 1496 details the tests required for each container to prove its ability to support superimposed loads [11]. The stacking strength, transverse rigidity, and longitudinal rigidity are the most crucial for structural integrity, and the testing details are shown in Figure 7.

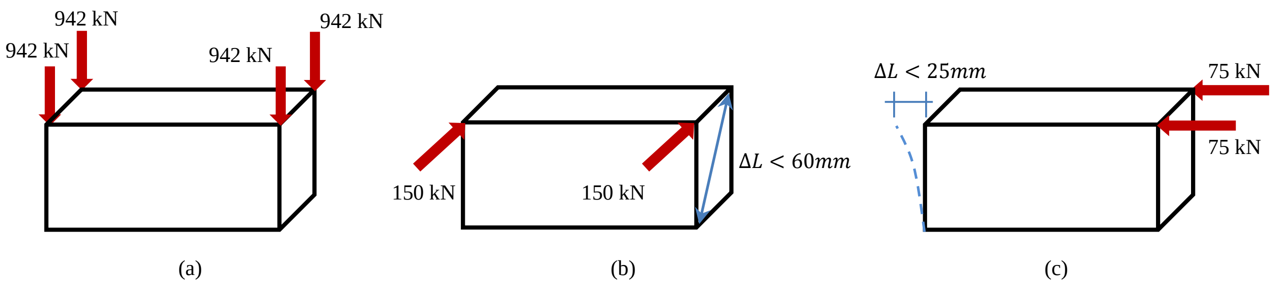


Figure 7. Standard Tests for ISO Shipping Container [11]: (a) Stacking, (b) Rigidity (Transverse), and (c) Rigidity (Longitudinal)

Table 2 compares the ISO testing loads and the loads considered in the analysis. The ISO axial load on each corner post represents the weight of nine-high stacking containers. The ISO lateral load was applied as an equivalent point load at each side frame and end frame. In the study, the maximum resultant wind load was computed for SC Design 2 since wind load is a function of height. The earthquake load which is based on the total weight of the structure is the same for SC Design 1 and 2. The lateral load on the side frame and end frame is governed by wind load. A comparison of the loads shows that ISO testing loads far exceeded the applied loads. Hence, the SC has sufficient capacity to support the superimposed loads.

Table 2. Comparison of ISO Testing [11, 28] and Container Loads on 20'HC

Structural element	ISO Testing (ISO 1496-1:1990)		SC Design 1			SC Design 2		
	Axial Dead (kN)	Lateral (kN)	Axial Dead (kN)	Wind (kN)	Earthquake (kN)	Axial Dead (kN)	Wind (kN)	Earthquake (kN)
Side frame	-	75	-	27	20	-	20	20
End frame	-	150	-	34	20	-	49	20
Corner post	942	-	18	-	-	18	-	-

Tables 3 and 4 summarize the governing D/C ratio for SC Design 1 and 2, respectively. All the members were adequate since the D/C ratio is less than one. The axial force in the corner posts governs. Note that vertical loads are transferred directly to the corner posts which are restrained laterally against buckling by the steel corrugated walls. The bending moments and shear forces in the top and bottom rails were minimum. The global results show that SCs have inherently high strength.

Serviceability was verified by checking the structure displacement. Figure 7 shows the allowable deflection for the SC as per ISO 1496. For the side frame, the lateral deflection of the top of the SC with respect to the bottom shall not exceed 25 mm. For the end frame, the lateral deflection of the top of the SC with respect to the bottom shall not cause the sum of the changes in the length of the two diagonals to exceed 60 mm. With the SC height of 2.89 m and width of 2.4 m, the allowable lateral deflection of the end frame was computed as 0.89 m. Table 5 shows the actual displacements of the side frame and end frame for the two SC designs which were well below the allowed deflection under the lateral loads. For two stacks of SCs with the simple layout considered, the SCs have sufficient strength and deformation capacity under strong wind and lateral load. This may not be true for multi-storied SCs under complex architectural lay-out and needs case-specific investigation.

Figures 8 and 9 show the wall stresses for SC Design 1 and 2, respectively, under the governing load combination of dead, live, and wind load. The side walls and end walls were very effective in resisting the lateral loads. For example, in Figure 8(a), when the SC was loaded in the x-direction, the side walls resist the load and were subjected to tension. In Figure 9(b), when the SC was loaded in the y-direction, the end walls resist the load and were subjected to tension as well. According to Giriunas et al. [20], the side walls and end walls are the strongest load resisting components when loaded in longitudinal and transverse direction, respectively. It is important to note that in Figure 9(b), the SC roof also contributed in resisting the load. This observation is in contrast to the result of Girunias et al. where they noted that the roof did not have structural contribution for lateral loads.

The effect of panel cuts and openings in SCs can be seen by comparing Figures 9(a) and 10. By moving the door opening 20 cm away from the edge, the stress decreased. Giriunas et al. [20] in their study showed that the lateral resistance of the SC is significantly reduced when entire walls in the direction of loading were removed and should be a consideration when modifying the SC for housing purposes. Bernardo et al. [19] recommended that vertical strengthening elements be added to compensate for the loss in original strength. Based on interviews conducted with people staying in a container office, it was found that a problem regarding extreme shaking during a strong typhoon is experienced. From the results of the structural analysis, reactions of the columns show upward forces when the SC model was subjected to wind loads. To minimize such a problem, the use of parapet is recommended. A parapet is a barrier which is an extension of the wall at the edge of a roof, terrace, balcony, walkway, or other structure. Normally, a parapet is provided in the roof to prevent the passage of air that could blow away the roof of a structure. In this case, to prevent the passage of air through the bottom of the SC home, a parapet can be installed.

Table 3. DC ratio of structural members for SC Design 1

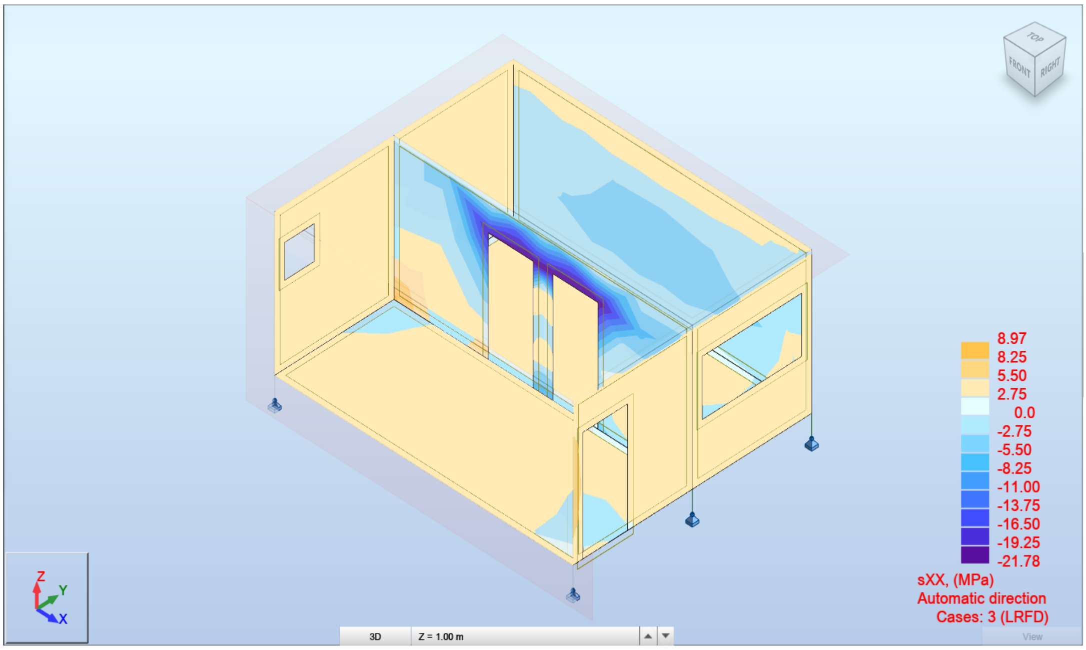
Member ID	Member Type	Governing D/C Ratio
1	Corner post	0.16
2	Corner post	0.25
3	Corner post	0.19
4	Corner post	0.30
5	Corner post	0.22
6	Corner post	0.40
7	Bottom beam	0.05
8	Bottom beam	0.20
9	Bottom beam	0.10
10	Bottom beam	0.15
11	Bottom beam	0.13
12	Bottom beam	0.15
13	Bottom beam	0.24
14	Top beam	0.02
15	Top beam	0.02
16	Top beam	0.00
17	Top beam	0.01
18	Top beam	0.05
19	Top beam	0.06
20	Top beam	0.02

Table 4. DC ratio of structural members for SC Design 2

Member ID	Member Type	Governing D/C Ratio
1	Corner post	0.30
2	Corner post	0.05
3	Corner post	0.24
4	Corner post	0.71
5	Corner post	0.60
6	Corner post	0.02
7	Corner post	0.05
8	Corner post	0.00
9	Bottom beam	0.43
10	Bottom beam	0.08
11	Bottom beam	0.46
12	Bottom beam	0.30
13	Middle beam	0.08
14	Middle beam	0.18
15	Middle beam	0.03
16	Middle beam	0.03
17	Top beam	0.02
18	Top beam	0.13
19	Top beam	0.06
20	Top beam	0.10

Table 5. Comparison of ISO [11, 28] and Container Lateral Deflection

	ISO Testing (ISO 1496-1:1990)	SC Design 1	SC Design 2
Side frame	25 mm	7 mm	6 mm
End frame	86 mm	15 mm	22 mm



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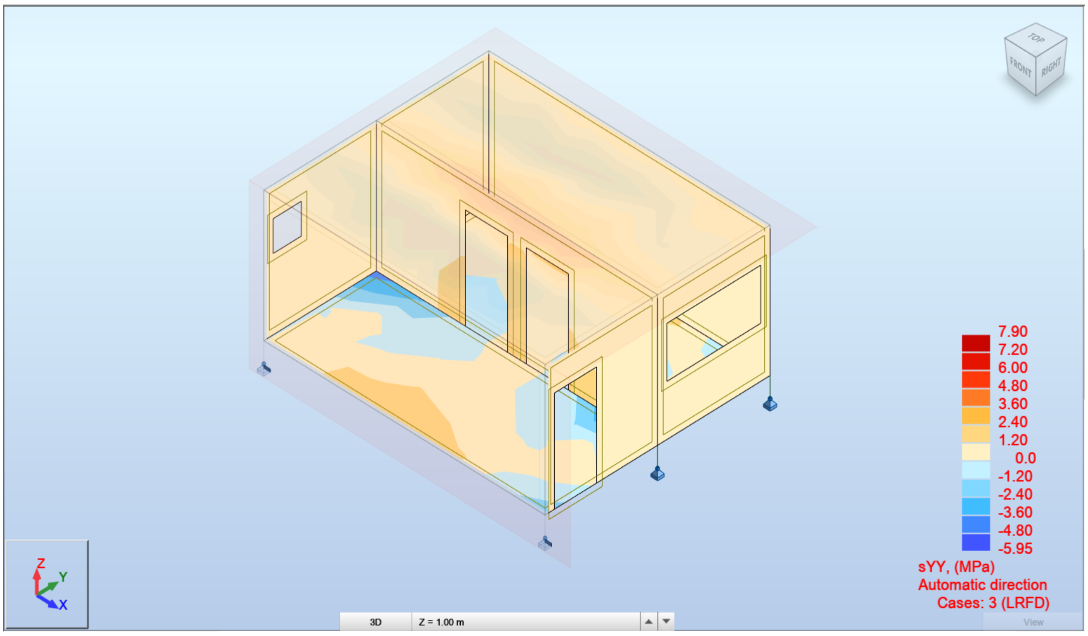
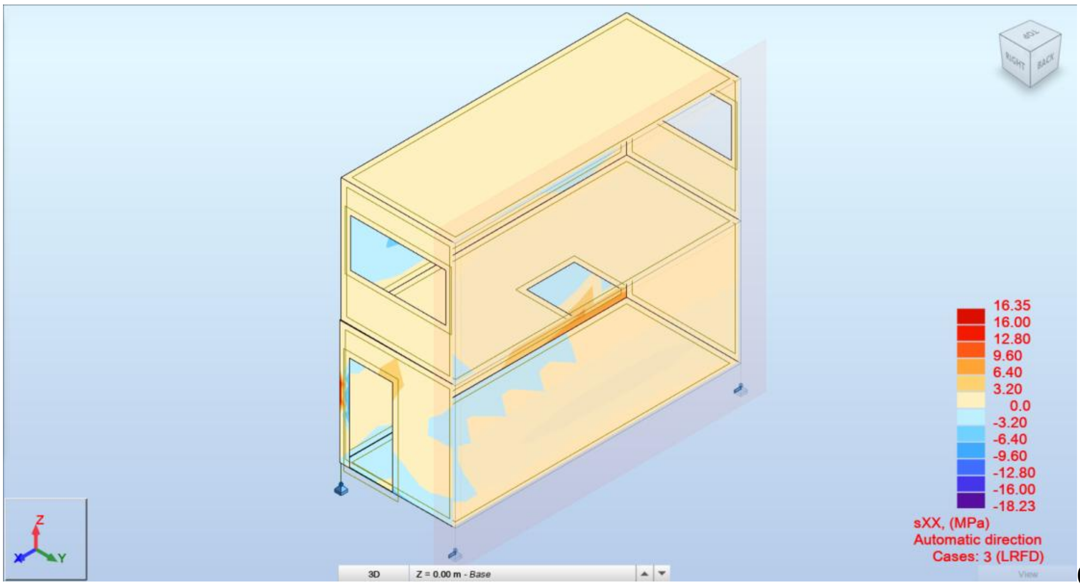


(b)

Figure 8. Stresses due to cuts/openings of SC Design 1: (a) x plane and (b) y plane



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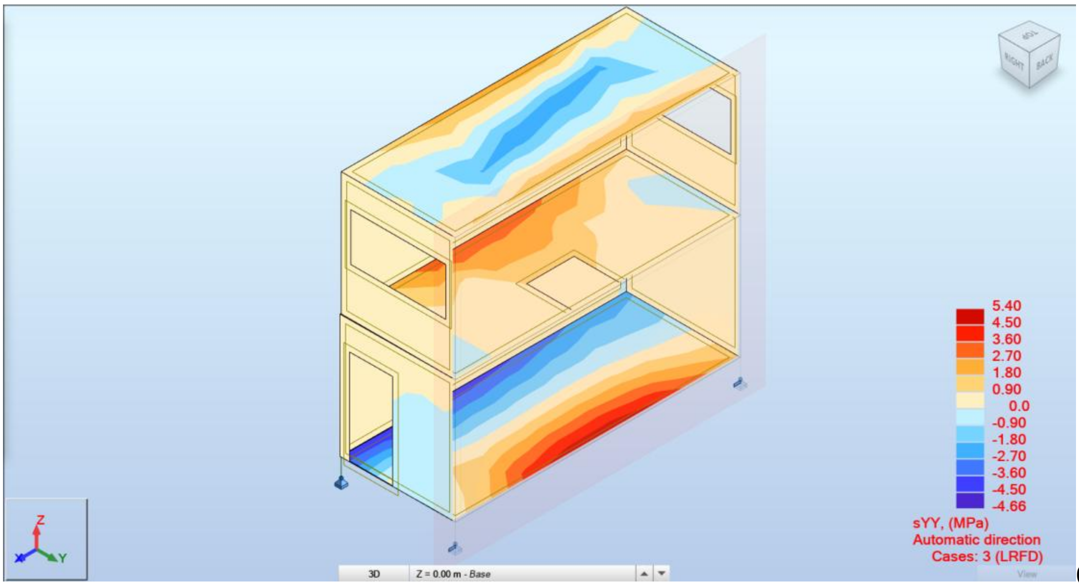


(b)

Figure 9. Stresses due to cuts/openings of SC Design 2: (a) x plane and (b) y plane

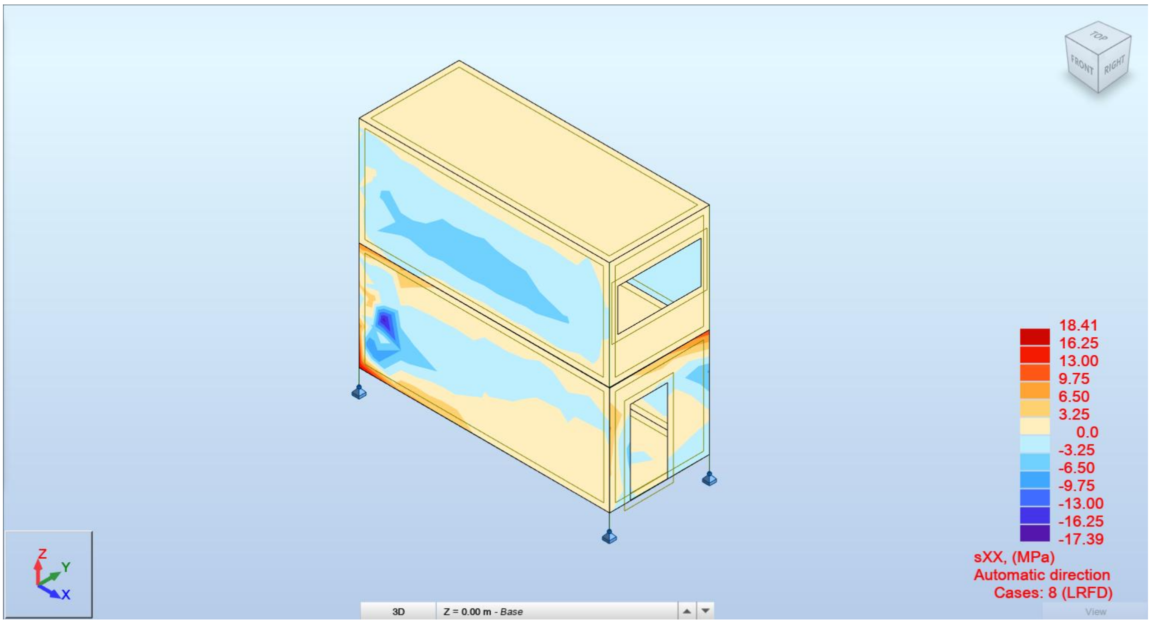


Figure 10. SC Design 2 reduction in wall stresses by moving cuts/openings away from edges

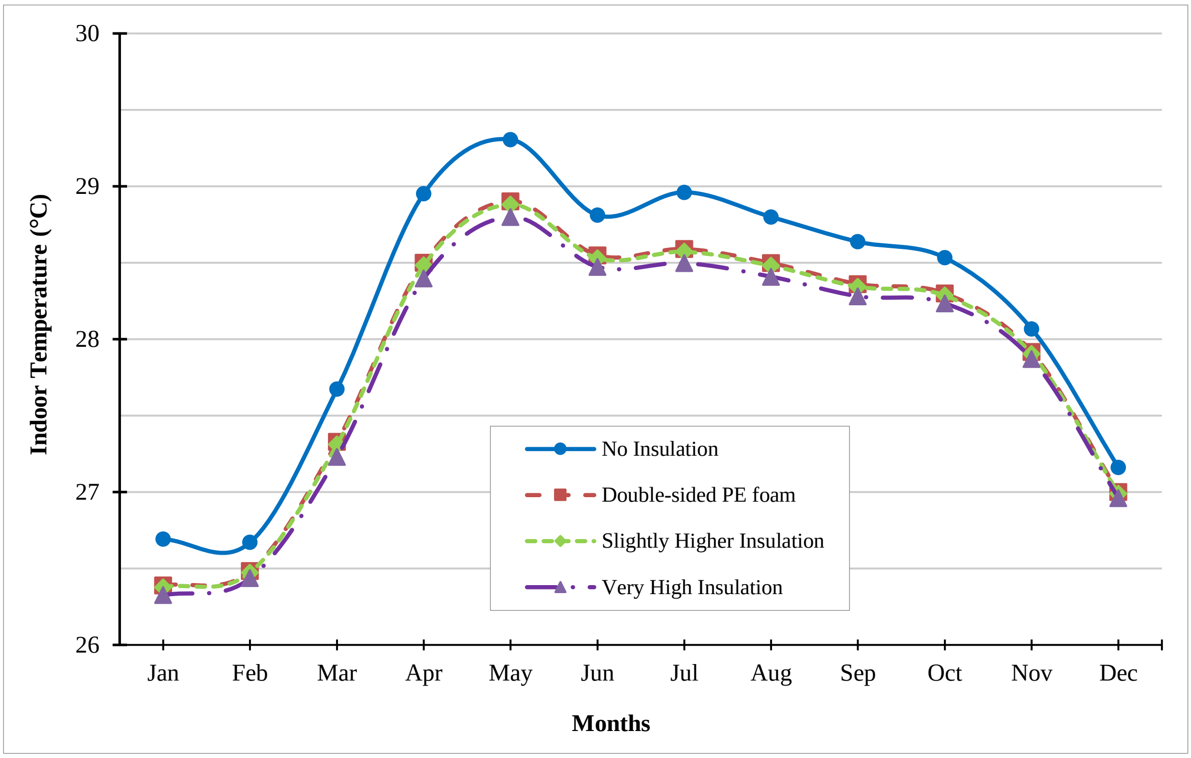
3.2. Results of Thermal Performance Assessment

Figures 11 and 12 show the mean monthly indoor temperature and indoor relative humidity, respectively, for SC Design 1 and 2 based on the building energy simulation. For both designs with uninsulated SCs, mean monthly indoor temperature ranges from 26.7 to 29°C while mean monthly indoor relative humidity ranges from 76 to 83%. ASHRAE 55 [39] recommends indoor air temperature of 23 to 27°C and relative humidity of 30 to 60% in the summer. Note that the months of Apr, May, Jun, and Jul are associated with the hot dry season of the country, with May having the highest temperature. The rest of the year is humid.

In a hot and humid climate, thermal comfort can be achieved by decreasing both temperature and humidity. Use of insulation lowers the indoor temperature by as much as 1°C (Figure 11) but further increases indoor relative humidity by as much as 2% (Figure 12) for both designs. Moreover, increasing insulation R-value does not significantly result in improving thermal comfort for both SC Design 1 and 2. Based on a PMV of ±0.5 and PPD of at most 20% [39], thermal comfort is achieved in the months of Jan, Feb, and Dec, when the temperature is low. These months are associated with the cold dry season of the country.

Since the months of Apr, May, Jun, and Jul have high temperatures, the metabolic rate, clothing insulation, and airspeed were adjusted to check if thermal comfort can still be attained. Their values were recorded given that one of the parameters from metabolic rate, clothing insulation, and airspeed was adjusted while other parameters were held constant. The results of these adjustments can be seen in Figures 13 to 15. The results show that the months of Apr, May, and Jun are the most critical months in thermal comfort for all four cases considered. Figure 13 shows that if clothing insulation of 0.5 clo and airspeed are held constant, the metabolic rate has to be lowered to a range of 1.30-1.35 mets to achieve thermal comfort. At this metabolic rate, constant walking and other higher metabolic activities could generate enough heat to reach thermal discomfort, especially in a household with five occupants. Figure 14 shows that at constant metabolic rate and airspeed, two of the three critical months in both design cases reached the required 0.25 clo, the minimum clothing insulation allowed. Although the lack of insulation in SC Design 1 failed in maintaining the minimum clothing insulation, all other forms of insulation still reached the minimum in the months of Apr and May. Figure 15 shows that to achieve thermal comfort, having airspeed towards the house higher than the actual airspeed will help the house reach thermal comfort. During the critical months, the deviation between the required and actual airspeed is significant, with May having the highest deviation. Considering Model 2 with double-sided PE foam insulation, SC Design 1 has a deviation of 2.97 m/s while SC Design 2 has a deviation of 3.1 m/s for the month of May. Comparing all other months and design considerations, it still shows that SC Design 2 has the higher deviation, making it the less desirable design case in terms of airspeed requirement.

Overall, the simulation results show that the thermal performance of SC Design 1 is comparable to SC Design 2. However, the SC is not compatible under a hot and humid climate even with the use of insulation materials. This was also observed by Jamaludin et al. (2021) in their study of providing bamboo as insulation for container construction in the hot and humid tropical climate of Malaysia [26]. Ismail et al. (2015) highlighted that in the hot and humid conditions of the tropics governed by high humidity level of more than 70% in the average and hot outdoor temperature which can exceed 32°C in daytime, major modification works are needed to ensure a thermally comfortable environment for such type of architecture [23]. According to Robinson et al. (2011) as cited in [23], SCs should be refurbished not only by installing appropriate layers of insulation for controlling thermal, acoustic, and fire protection, but also equipping it with suitable vapor barriers, internal fittings, and finishes that suit local climate.



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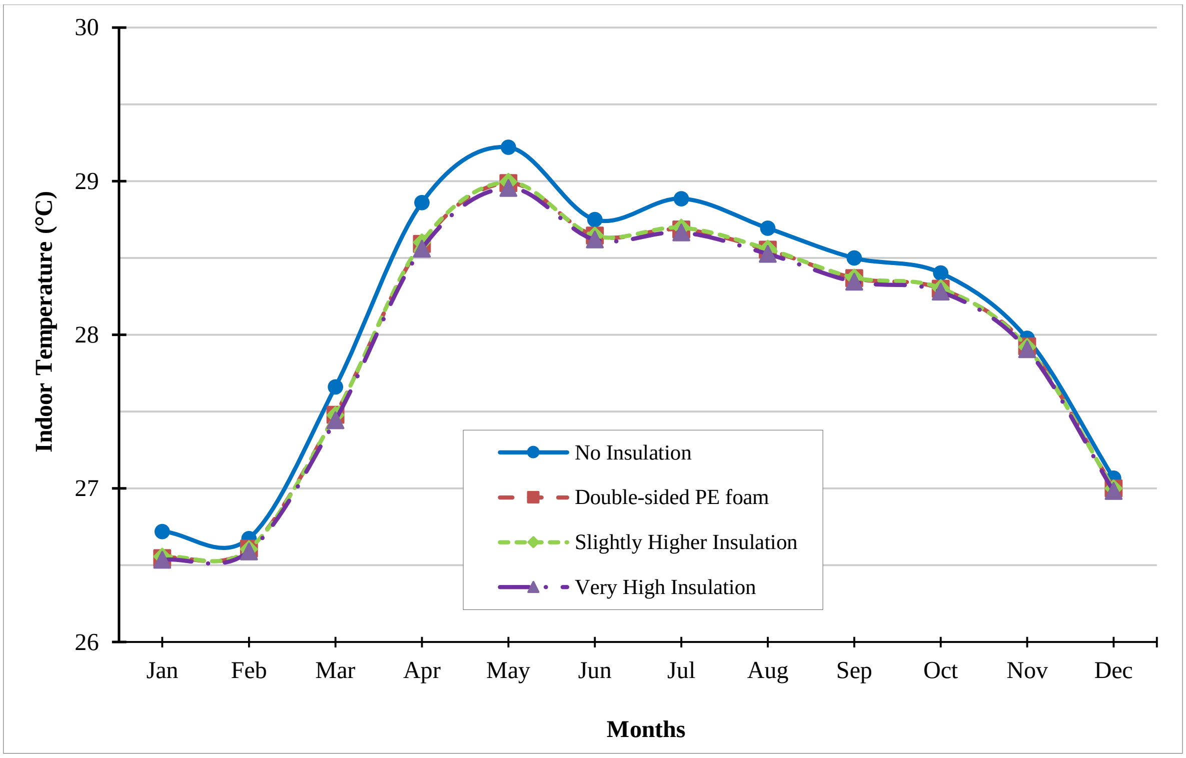
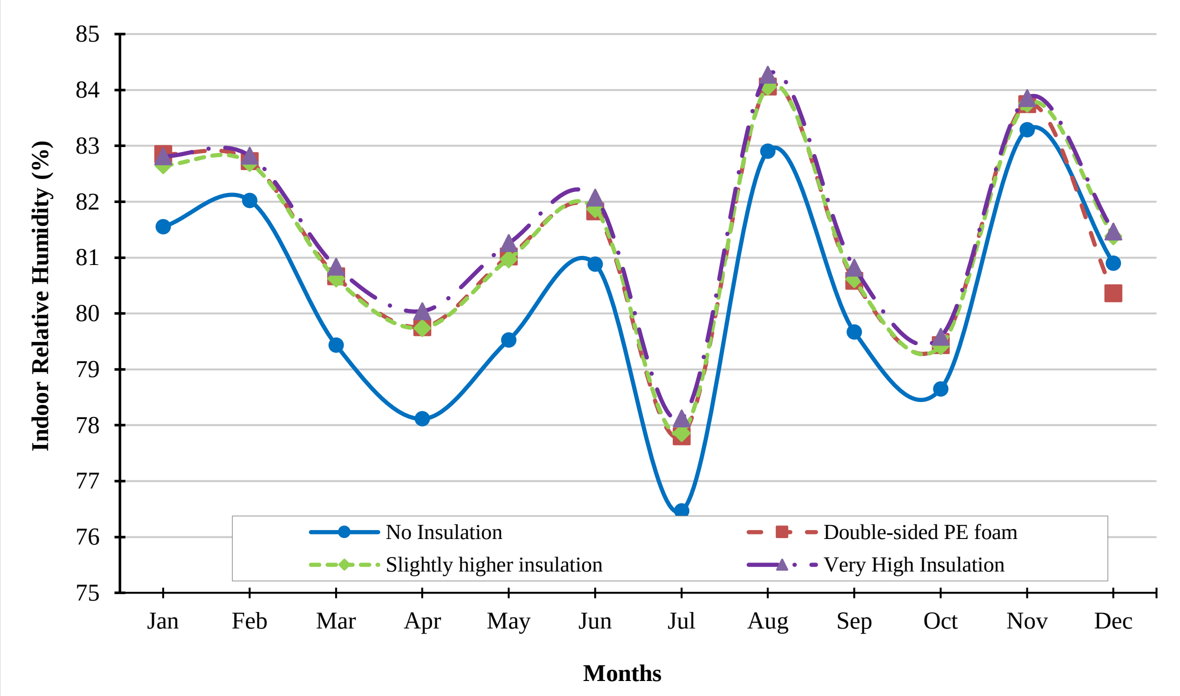


(b)

Figure 11. Effect of varying insulation on indoor temperature: (a) SC Design 1 and (b) SC Design 2



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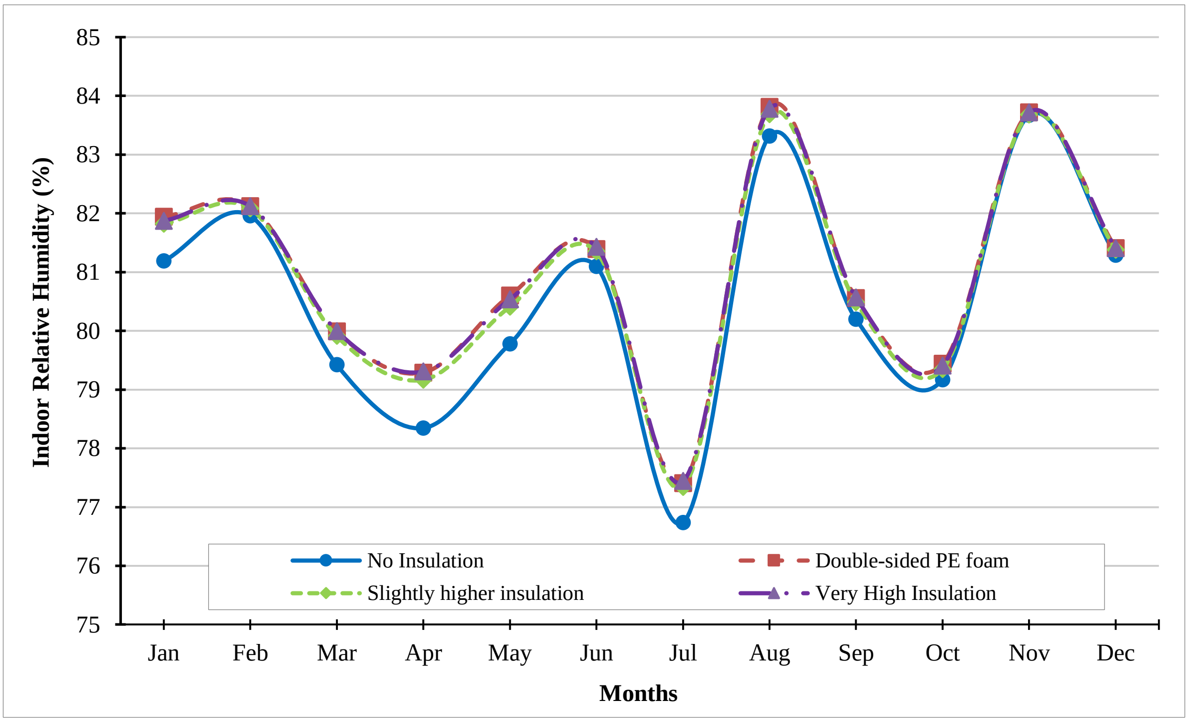


(b)

Figure 12. Effect of varying insulation on indoor relative humidity: (a) SC Design 1 and (b) SC Design 2

To check if thermal comfort can still be improved, two other parameters such as structure orientation and window properties were varied. SC design 1 and 2 were oriented in the S, SW, W, NW, N, NE, E, and SE directions. Noting that the prevailing wind during the summer months of Apr, May, and Jun come from the East, called the easterlies [22], the N and S orientation yielded the lowest indoor temperature but the highest relative humidity. The difference, however, is not that much with that obtained for the other directions. For both designs, the orientation of the container does not improve thermal comfort. This is in contrast to the results of Shen et al. [27], wherein their thermal comfort analysis shows that the optimal building orientation is in the direction perpendicular to the direction of the prevailing wind during summer months.

Windows allow the increase and decrease of indoor relative humidity through occupancy-controlled natural ventilation. Windows can also prevent solar heat gain through glazing with low-emissivity (E) coating and conductive heat through insulated frames. From the results of the study, having closed windows or any scheduled natural ventilation increases both the indoor temperature and indoor relative humidity. The use of special triple pane, insulated windows did not also improve the thermal conditions of the SC house. Shen et al. [27] recommended the use of high-performance windows that must be well-shaded by both overhang and operable shutters and facing prevailing wind direction.

For SCs intentionally built for shelter and for those in the low-income groups in the tropics who usually do not resort to air-conditioning for cooling but only depends on natural ventilation with the assistance of mechanical fans to reduce the cost of living, other alternatives may be explored. This may include green roof and walls [25], use of reflective surface with aluminum hybrid turbine ventilator for roof without insulation [23], and architectural passive cooling measures such as use of overhang and operable shutters among others [27].

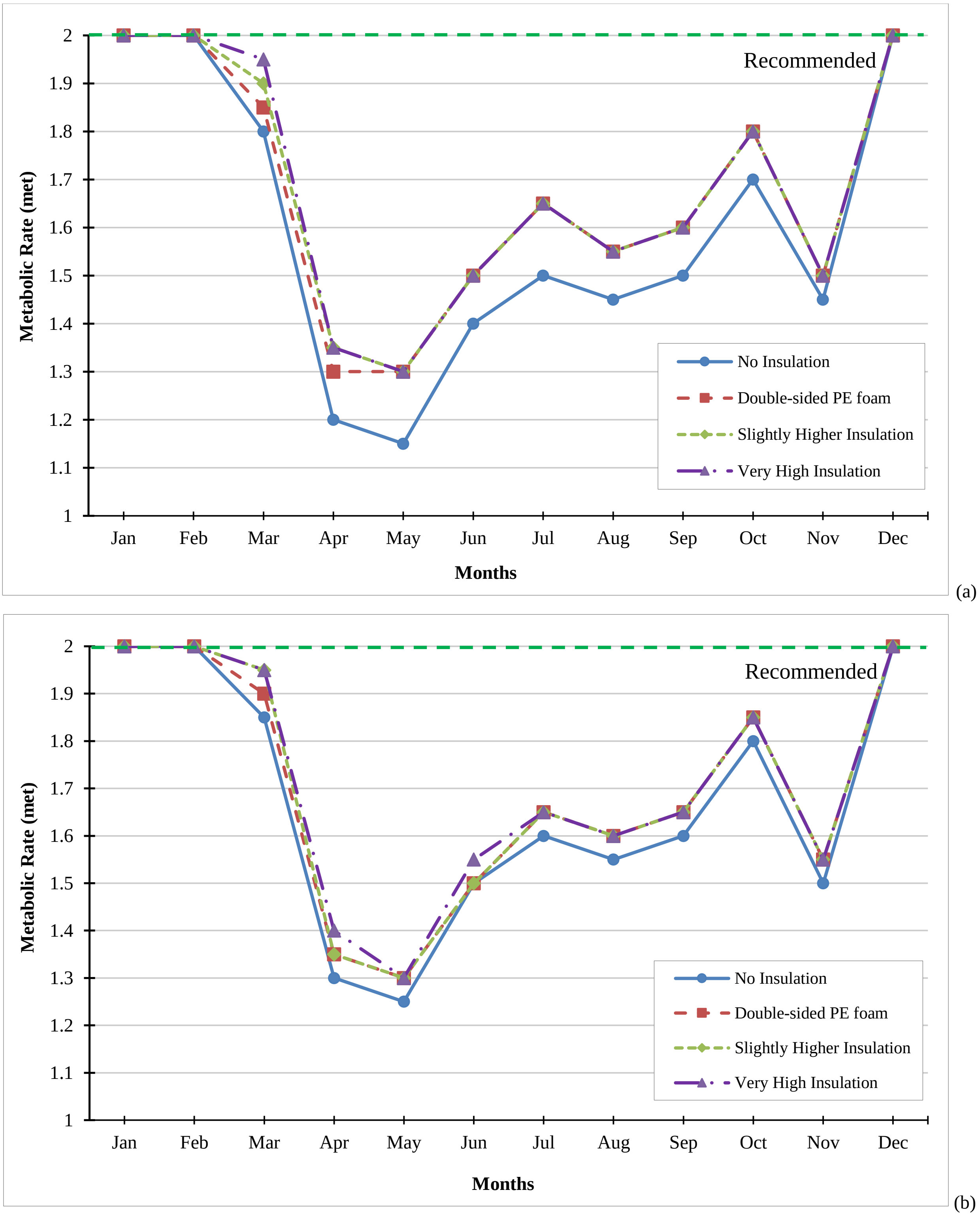
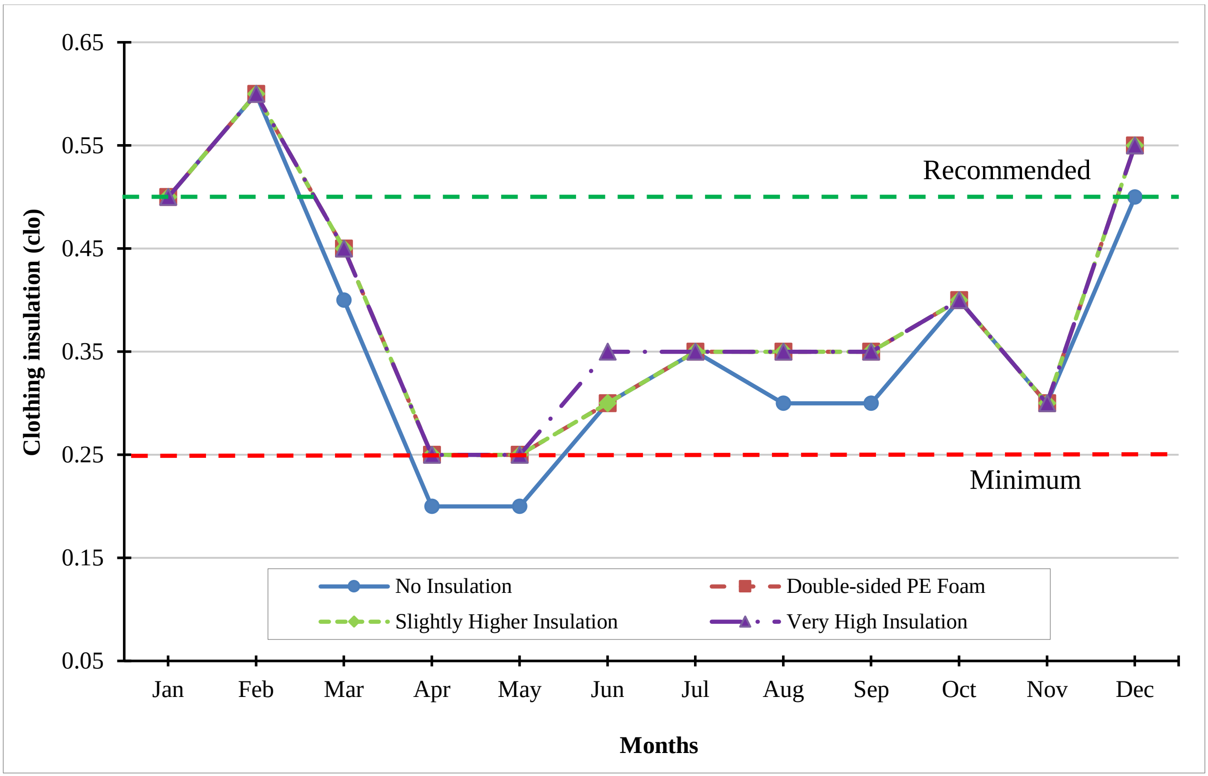
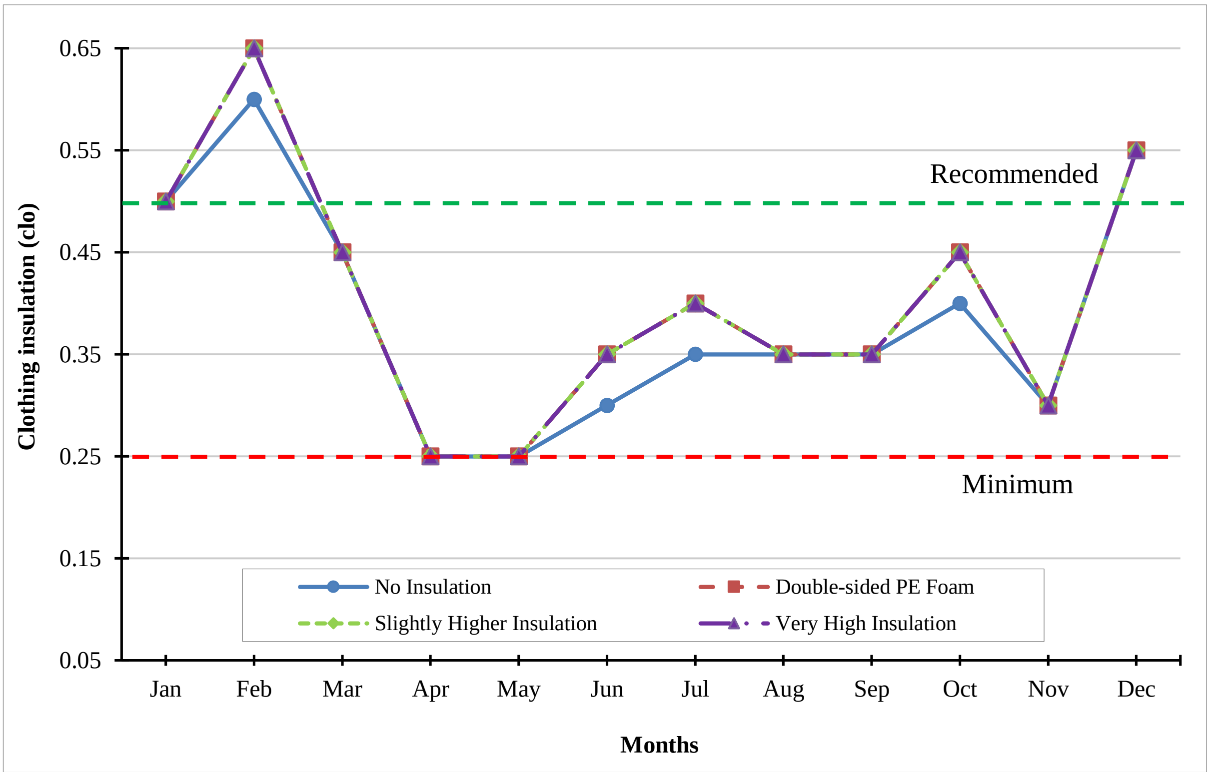


Figure 13. Effect of varying insulation on metabolic rate: (a) SC Design 1 and (b) SC Design 2

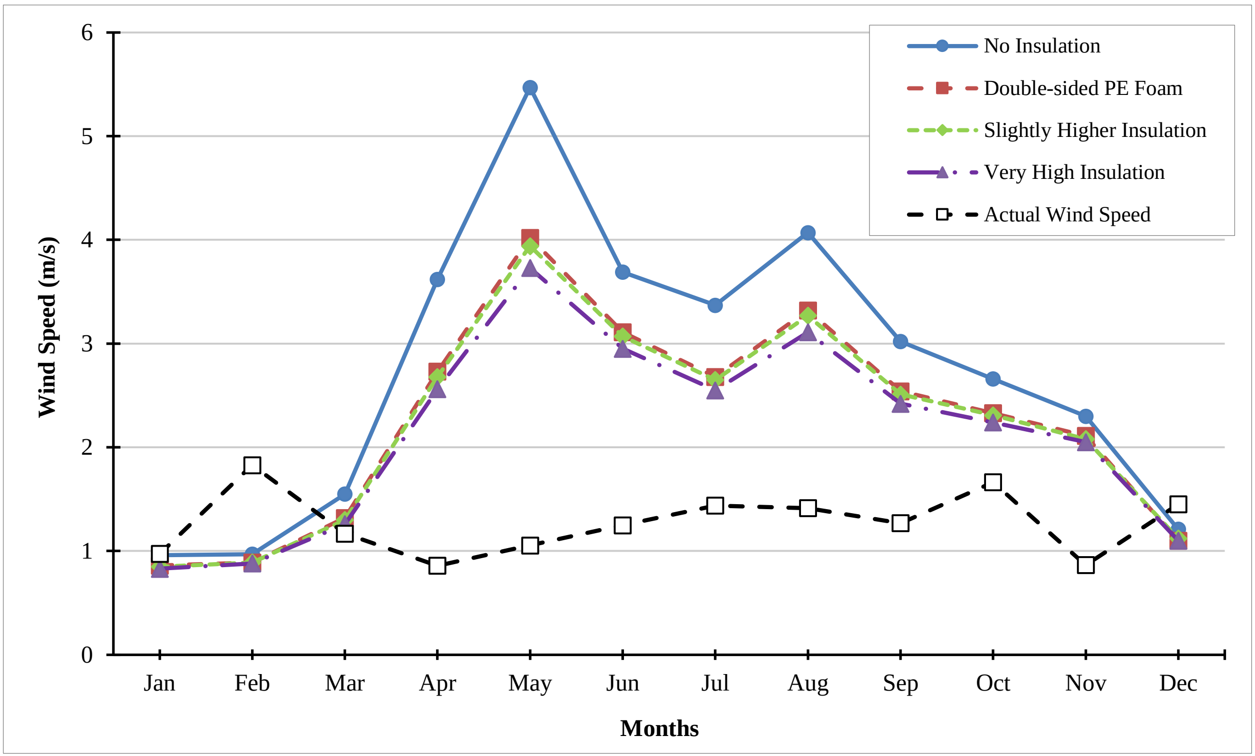


(a)



(b)

Figure 14. Effect of varying insulation on clothing insulation: (a) SC Design 1 and (b) SC Design 2



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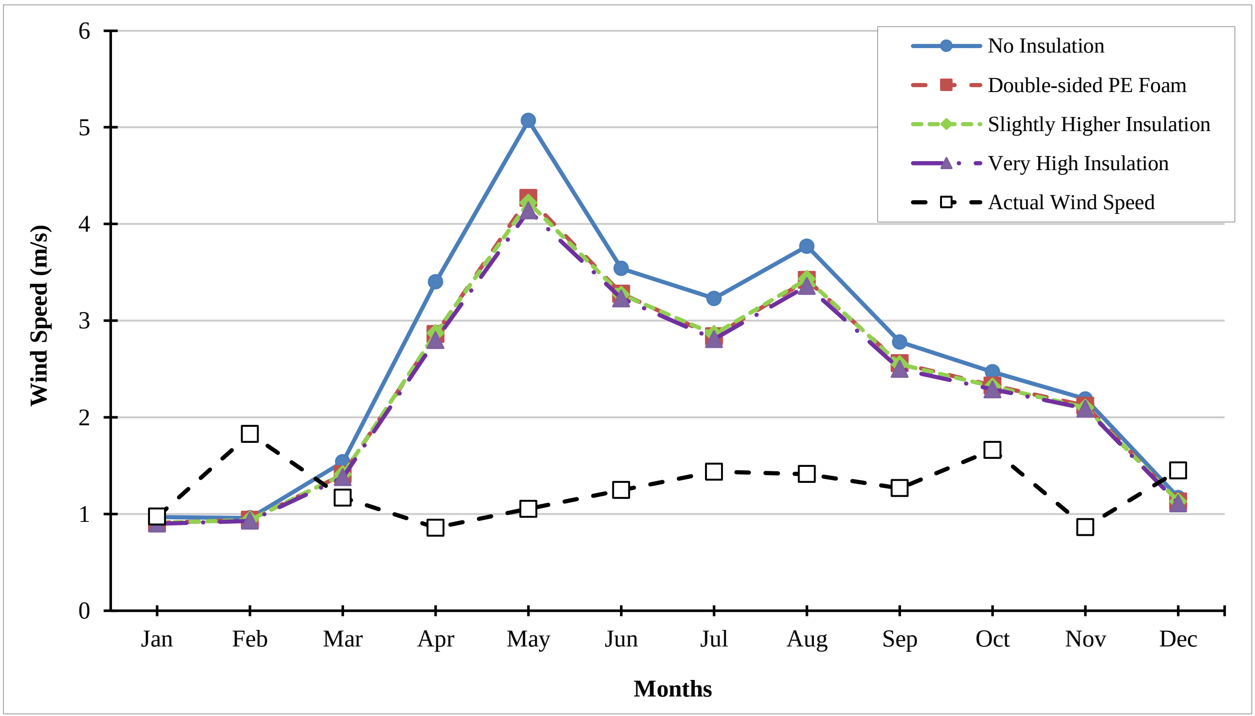

(b)

Figure 15. Effect of varying insulation on wind speed: (a) SC Design 1 and (b) SC Design 2

4. Conclusions

The study investigated the use of SCs as a means of providing shelters to disaster victims. Two design layouts were created using two 20' HC containers. SC Design 1 is a one-story shelter, while SC Design 2 is a two-story shelter. To assess the structural performance, finite element analysis was conducted. All members adequately satisfy the strength and serviceability requirements. The effect of panel cuts/openings on the strength of the SCs was also investigated. Stresses due to the cuts were minimized when the cuts/openings were placed far from the corner posts.

To assess the thermal performance of SC shelters, building energy simulation was conducted. The study simulates the two designs created while considering increasing insulation R-value in the designs. Based on ASHRAE Standard 55, the thermal conditions of both SC designs complied only during the cold dry months of Jan, Feb, and Dec and are most critical during the hot dry months of April and May. Thermal insulation is indispensable in SCs for habitation. However, different insulation considerations gave near similar results for both SC designs. For the critical months, thermal comfort can be achieved through lower metabolic activity throughout the day, lower clothing insulation, and higher airspeed.

Two other parameters such as structure orientation and window properties were investigated to check if thermal comfort can still be improved. For both SC designs, the orientation of the container does not improve thermal comfort. Moreover, even having glazed windows, scheduled natural ventilation, or closed windows increases both the indoor temperature and indoor relative humidity. The thermal performance of SC Design 1 is similar to SC Design 2. To ensure thermal comfort throughout the rest of the year, other alternatives should be explored to make the SC comfortable. This study has shown the feasibility of using SCs as building construction modules. SCs have inherently high strength and can withstand strong wind and earthquake. However, more work needs to be done on making SCs thermally comfortable in hot and humid climates especially for those in dire need of habitable space.

5. Declarations

5.1. Author Contributions

Conceptualization, R.G.Z., V.M.N.D., and M.H.T.C.; methodology, R.G.Z., V.M.N.D. and M.H.T.C.; formal analysis: J.R.M.M., and P.J.M.V.; investigation, J.R.M.M. and P.J.M.V.; writing—original draft preparation, R.G.Z; writing—review and editing, M.S.M. and M.B.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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