Final version for publication

Effect of Built-Form Configuration on Energy and Structural Performance of Skyscraper Buildings

Mohamed Ali milad Krem[1], Simi T. Hoque[2], Sanjay R. Arwade[3]

ABSTRACT

The design of high performance buildings is becoming increasingly complex. Efforts are being made by engineers and architects to reduce the environmental impact of buildings to conserve resources and secure our energy future. It has been suggested that for each of the four Koppen's climate zones (arid, tropical, temperate, and cool) (Kottek M. et al 2006) there exists an optimal building morphology that defines floor plan geometry and placement of the primary structural cores, which contains major mechanical services and vertical transportation conduits.

This paper presents a quantitative study of the effect of building morphology on the energy performance of high rise buildings in each of the four climate zones. It addresses the implications of the various building morphologies for building structural performance, an effect which has been largely neglected in previous considerations of building morphology and energy performance.

The energy analysis is performed using Autodesk Ecotect Analysis 2011, and the structural calculations are made by hand. Four building morphologies are investigated, each representing a high rise commercial building with equivalent area, height, and material usage. Results present annual heating and cooling loads, the structural lateral stiffness, and the susceptibility of the building to torsional action under wind loading.

KEYWORDS

Morphology, sustainability, energy consumption, asymmetry

---

[1] Mohamed Krem, PhD Candidate, Civil and Environmental Engineering UMass-Amherst, MA, US

[2] Simi T. Hoque, Assistant professor, Department of Environmental Conservation, UMass-Amherst, MA, US

[3] Sanjay R. Arwade, Assistant professor, Civil and Environmental Engineering UMass-Amherst, MA, US

1. INTRODUCTION

Improving the energy efficiency of medium- to high-rise buildings is a key component in increasing the sustainability of the built environment. More than one-third of the world's energy consumption is attributed to the construction and building industry (Straube 2006). Given the current global energy crisis, there is a critical need to design and construct buildings that are more sustainable. Sustainable buildings minimize building resource consumption, operations and life cycle costs, and improve occupant health and comfort (United States Green Building Council 2008).

Substantial progress has been made towards improved energy efficiency through design and technological innovations such as passive ventilation systems, daylighting and sun shading, high performance heating, cooling, and ventilation (HVAC) systems, and the introduction of novel materials to the building envelope. However, the impact and influence of the structural system on building energy efficiency has been largely neglected and is the focus of this paper. We consider whether structural and energy performance considerations can be integrated and optimized concurrently, and we analyze tradeoffs in the design of structural systems for both structural and energy performance.

This analysis is predicated on the proposition that the structural system of a building can be optimized to improve energy efficiency in addition to resisting gravity and lateral loads. In his book *The Green Skyscraper (*Yeang 1999)*,* architect Kenneth Yeang suggests that in different climate zones the structural core/walls should be arranged to reduce the yearly energy consumption of the building. Furthermore, he argues that the shape of the building footprint should be modified based on the climate zone in which the building is to be constructed (Figure 1). In Yeang's analysis, three parameters are varied – (1) the shape of the building floor plan, (2) the placement of the structural core/walls, and (3) the orientation of the building floor plan. The first two of these parameters have clear implications for structural performance since buildings with asymmetric distribution of stiffness are known to be susceptible to damaging torsional modes of vibration when subjected to wind or earthquake loading. However, Yeang does not address the implications of different footprints and core/walls placements on structural performance. As for the third parameter, building orientation has much less effect on the structural performance unless the building is located where wind direction is strongly biased.

In the present study, we consider two parameters (the shape of the building footprint and the placement of the structural core/walls), which we, together, call the building morphology, and the influence of the morphology on energy performance. While material choice can have potentially significant effects on environmental and structural performance, we control for this variable in order to focus on the relationship between building morphology and energy efficiency.

Previous studies have shown the potential for structure to play a positive role in influencing the energy performance of buildings. For example, Mak et al (2007) investigated the effect of wing walls on passive ventilation and found potential synergies between the structure and environmental performance.

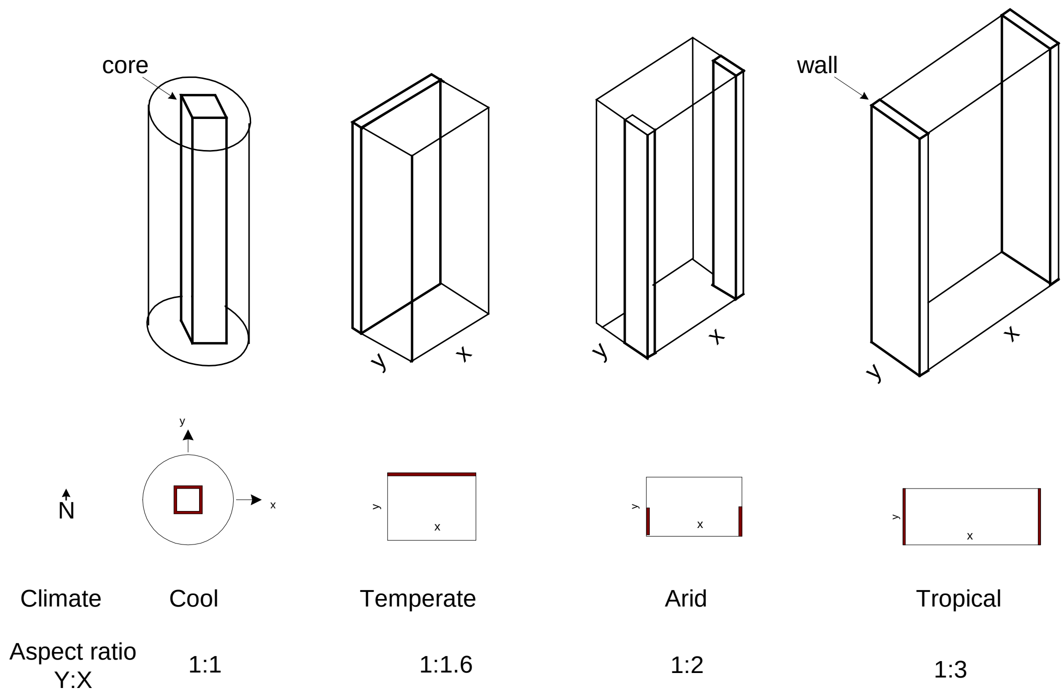


Figure 1 Proposal by K. Yeang for optimal floorplan and placement of structural core/walls to minimize building energy consumption in four climate zones

Additionally, structural engineers have made substantive efforts to design sustainable structures. Anderson & Silman (2009) and Webster (2004) identify how the structural engineer may work with an integrated design team of architects, engineers, builders and owners to make the structure sustainable. The Structural Engineering Institute of the American Society of Civil Engineers has recently published *Sustainability Guidelines for the Structural Engineer* (Kestner et al .2010), which emphasizes material selection and life cycle cost analysis as the basis for structural sustainability. These publications promise to significantly affect the way that structural engineering is practiced, yet neither directly addresses the interplay of structural form and energy efficiency, which is our primary interest.

In the following sections we define our problem to be the evaluation of the structural and energy performance of four different building morphologies in four different climate zones. We then present the results of structural and energy consumption calculations for each of the sixteen morphology/climate scenarios and finally discuss the results and present our conclusions.

1.1. Problem Statement

In this study, as in Yeang's, two main characteristics are modulated to optimize energy performance: the position of the vertical structural core/walls and the shape of the building footprint. All other morphological descriptors such as the square footage, number of stories, building height, occupancy, operating schedules, and envelope materials, are held constant across the four building types. All are 200 m in height, 50 stories that are 4.0 m floor-to-floor height, and have a total conditioned floor area of 135000 m^2. Figure 2 shows the plan views of the buildings and the locations of the primary mass (opaque surfaces) and the glazing walls (transparent surfaces) for each configuration. The primary material for the structural core/wall is reinforced normal weight concrete, and the glazed (curtain) walls are two layers of standard glass with 10% metal framing. To simplify the analysis of the energy consumption, we have neglected the effect of surrounding buildings and of building orientation, in essence assuming that the buildings are erected on flat open ground and are aligned with the cardinal directions.

The materials selected for the exterior envelope of all four models meet the requirements for thermal resistance of the 2009 International Energy Conservation Code (IECC 2009), for each specific climate zone. There are three different material palettes (with associated thermal resistances) for the four buildings. In other words, there is a prescribed material palette for buildings in the tropical zone 1, for buildings in the temperate and arid zones (both zone 3), and for buildings in the cool zone 5. Envelope cross sections and material thermal resistances are presented in Table 1.

All four building morphologies are simulated in each of the four major climate zones (cool, temperate, arid, and tropical, according to the Koppen classification). Additionally, we have selected specific cities as representative of the conditions in each climate zone, and use the climatic conditions at these four cities in the energy performance simulations: Boston, Massachusetts for the cool zone, Sacramento, California for the temperate zone, Las Vegas, Nevada for the arid zone, and Honolulu, Hawaii for the tropical zone, The climate characteristics for the representative cities are provided in table 2 (U.S. Department of energy 2011).

Building energy consumption is highly dependent on occupancy and scheduled usage of the interior space. Since our goal is to isolate the influence of building morphology on energy consumption, we assume that occupancy and scheduling characteristics are constant across all climate zones and building types. Specifically, we treat the thermostat range, internal design conditions, occupancy, infiltration rate, and hours of operation as fixed control variables (Table 3).

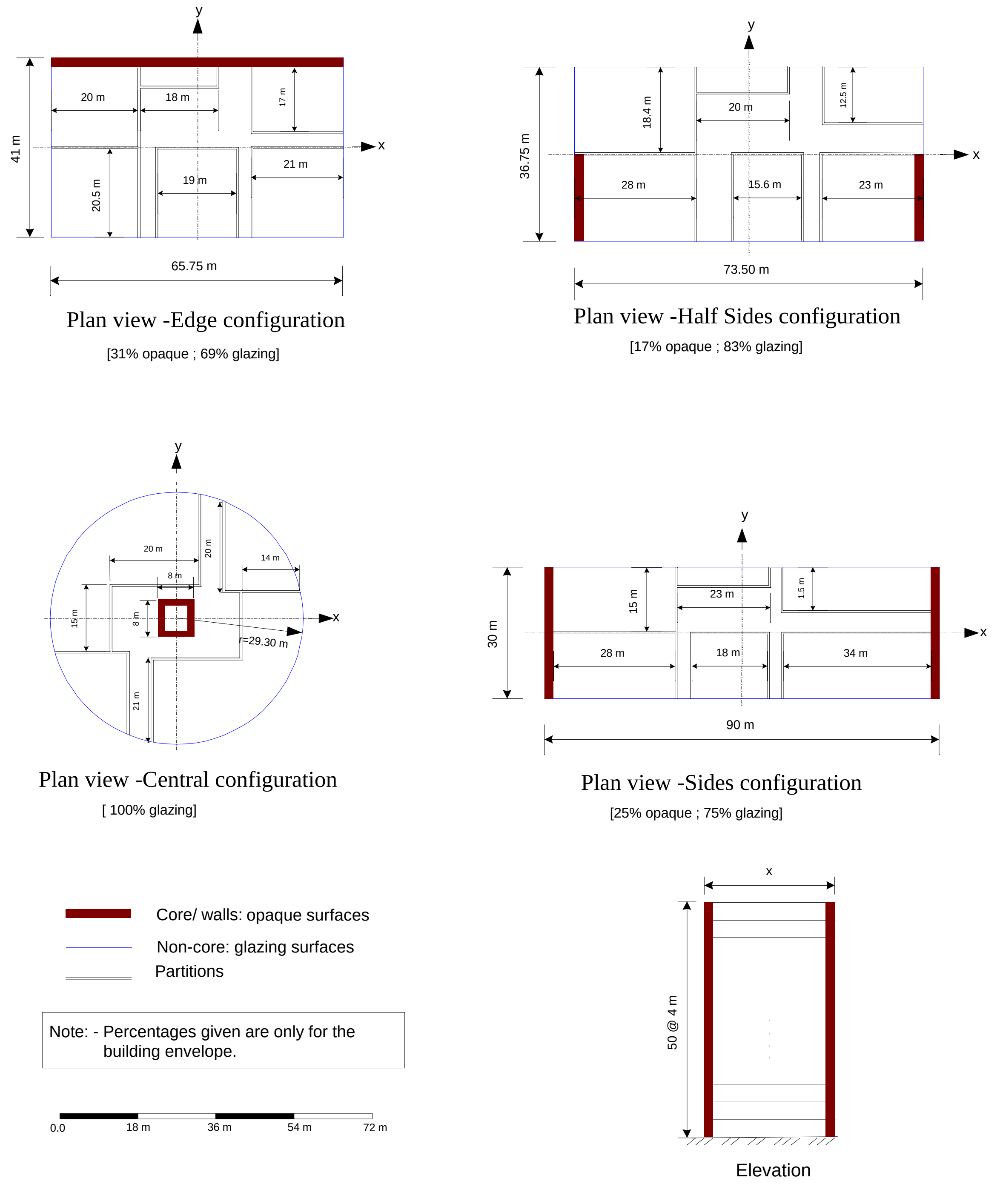
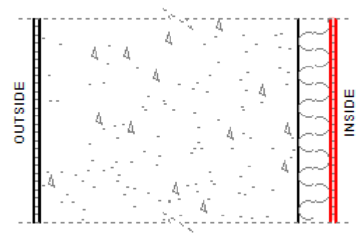
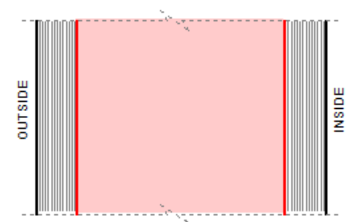
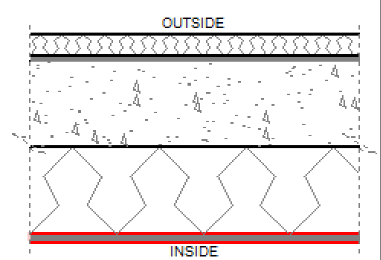


Figure 2 Plan views and an elevation of the buildings

Table 1 Envelope cross sections and thermal resistance of the constituent materials

Element	Material			Layers	Zone 1		Zone 3		Zone 5	
	Zone 1	Zone 3	Zone 5		U-value Btu /hr·ft²·°F	R-value hr·ft²·°F/Btu	U-value Btu /h·ft²·°F	R-value hr·ft²·°F/Btu	U-value Btu /hr·ft²·°F	R-value hr·ft²·°F/Btu
Core walls	*450 mm concrete III	450mm concrete III 22 mm polystyrene foam 10 mm plaster in either side	450 mm concrete III 45 mm polystyrene foam 10 mm plaster in either side		0.29	3.56	0.13	7.56	0.086	11.57
Glazing walls	*6 mm single glazed metal framing	6 mm double glazed metal framing, 15 mm gap with low-conductance gas fill	6 mm double glazed metal framing, 13 mm gap with low-conductance gas fill		1.2	0.83	0.60	1.64	0.45	2.20
Roof	27 mm Aggregate 6 mm asphalt 100 mm concrete III 19 mm poly. foam 10 mm plaster	27 mm Aggregate 6 mm asphalt 100mm concrete III 27 mm poly. foam 10 mm plaster	27 mm Aggregate 6 mm asphalt 100mm concrete III 27 mm poly. foam 10 mm plaster		0.065	15.3	0.047	21	0.047	21

* The element would consist of some layers only that shown in the layers column

(Continue)

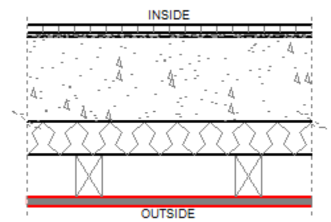
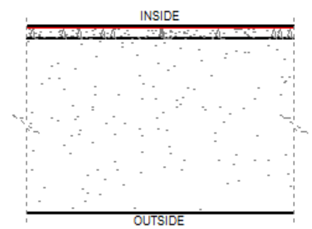
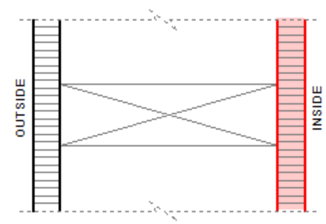
Element	Material			Layers	Zone 1		Zone 3		Zone 5	
	Zone 1	Zone 3	Zone 5		U-value Btu /hr·ft^2·°F	R-value hr·ft^2·°F/Btu	U-value Btu /hr·ft^2·°F	R-value hr·ft^2·°F/Btu	U-value Btu /hr·ft^2·°F	R-value hr·ft^2·°F/Btu
Floor suspended concrete	10 mm ceramic tiles 5 mm screed 100 mm suspended concrete floor 50 mm air gap 10 mm plaster ceiling underneath	10 mm ceramic tiles. 5 mm screed 100 mm suspended concrete floor 20 mm polystyrene 50 mm air gap. 10 mm plaster ceiling underneath	10 mm ceramic tiles. 5 mm screed 100 mm suspended concrete floor 40 mm polystyrene 50 mm air gap. 10 mm plaster ceiling underneath		0.32	3.13	0.151	6.59	0.047	10.13
Slab on ground	100mm concrete 5 mm screed 10 mm ceramic tiles	100mm concrete 5 mm screed 10 mm ceramic tiles	100mm concrete 5 mm screed 10 mm ceramic tiles		0.155	6.5	0.155	6.5	0.155	6.5
Partition	80mm framed wall as air gap 10mm plaster board either side	80mm framed wall as air gap 10mm plaster board either side	80mm framed wall as air gap 10mm plaster board either side		0.39	2.59	0.39	2.59	0.39	2.59

Table 2 Description of the characteristics of the climate zones for the representative cities

Characteristics \ City		Boston [Cool zone]	Sacramento [Temperate zone]	Las Vegas [Arid zone]	Honolulu [Tropical zone]
Average temperatures	high	23.3 °C	24 - 32 °C	34 - 40 °C	27-32 °C
	low	-1.5 °C	7.7- 16 °C	21–26 °C	19-24 °C
Dry bulb temperature	maximum	37.2°C [on Jul 9]	42.0°C [on Jun 14]	44.4°C [on Jul 4]	33.3°C [on Sep 2]
	minimum	-20.0°C [on Jan 23]	-2.0°C [on Feb 2]	-3.3°C [on Feb 16]	13.3°C [on Feb 12]
Annual degree-days [18°C baseline]	cooling	490	670	1904	2524
	heating	3120	1436	1234	0.0
Average daytime		11 hr, 45 min	12 hr, 24 min	11 hr, 15 min	12 hr
Average nighttime		12 hr, 15 min	11 hr, 36 min	12 hr, 45 min	12 hr

Table 3 Thermal analysis conditions

Parameters		Values	Description
Active system		Full Air conditioning	*Active system for providing heating and/or cooling*
Thermostat range		18 – 26 ^{o}C	*comfortable range*
Occupancy	People	12 m^2/p	*office - typical square area for one person*
	Activity	70 W/p	*sedentary*
Internal design conditions	clothing	1 clo/p	*light business suit*
	Humidity	60%	*comfortable Humidity*
	Air speed	0.5 m/s	*pleasant breeze*
	lighting level	300 lux	*luminous flux per unit area*
Infiltration rate	Air change rate	0.5 /hr	*office - typical value*
Internal heat gain		10 W/ m^2	*lighting and equipment*
Hours of operation		Schedule	*8am-18pm*

1.2. Thermal Analysis (Energy Performance)

In the following sections, we refer to the proposed configurations depending on where the structural core/walls are placed: ‘Central’; ‘Edge’; ‘Half Sides’; and ‘Sides’.

1.2.1. Modelling. Autodesk’s Ecotect 2011 energy simulation package was used for the thermal analysis. Ecotect 2011 is a comprehensive concept-to-detail sustainable building design tool; it is a popular program used by many architects, the modelling procedure is simple, it is easy to manipulate the properties of models rapidly, and analysis time is reasonable for large models. Briefly, the procedure using Ecotect starts with creating a three dimensional shell that represents the building form. This can be done in one of two ways: (1) draw plans representing the boundary of the rooms, continuing room by room to form a 3D model; or (2) import the model as gbXML file from a different 3D modelling program such as Revit. For this analysis, we prepared the building's geometry in Revit 2010, and then imported the 3D model as surfaces and rooms to Ecotect 2011. After the import, thermal properties are assigned to the building's envelope and the analysis proceeds. The basic material of an element (concrete wall, slab, glazing wall, etc.) is assigned and then the resistance (R-value) of the insulation is applied, according to specifications of IECC code as presented in Table 1. The next step is to assign a weather file which corresponds to the climatic zones selected for this study and to provide occupancy and scheduled usage data. Following input and setup of the model, the program can calculate monthly and annual heating and cooling loads based on the given climate conditions.

1.2.2. Modelling Assumptions. For the purpose of this study, several assumptions are made: a) All the buildings have equivalent square footage, height, material usage, and thermal properties; b) All the buildings are at right angles to the cardinal directions; c) The circular shape of Central configuration has been replaced by a dodecagon (12-sided) shape with equivalent floor area as shown in Figure 3. Visualizations of the Ecotect models in 3D are shown in Figure 4.

1.2.3. Thermal Analysis. The thermal analysis involves examining each of the four models (Central, Edge, Half Sides, and Sides) in each of the four climatic zones (cool, temperate, arid, and tropical). This constitutes sixteen different simulation runs, each of which requires approximately twenty-four hours to complete. For each climate zone the four models are tested with consistent thermal properties and weather data. That is, the only differences among the four runs in the same climate zone are the aspect ratio and the placements of the structural cores/walls. Ecotect calculates the effect of solar insolation on the heating/cooling loads of each building which differs among the climate zones. For example, in the tropical zone the heating demand is negligible (effectively zero) throughout the year (U.S. Department of energy 2011) and cooling loads dominate. It would follow, therefore, that in order to reduce cooling loads in the tropical zone direct heat gain as a result of solar insolation must be minimized. In this case Yeang suggests shading the building's east and west sides. Figure 5 shows the sun-path diagram and how the building is shaded by its side walls (location at 12:15 pm, 20th August, Honolulu, Hawaii-USA).

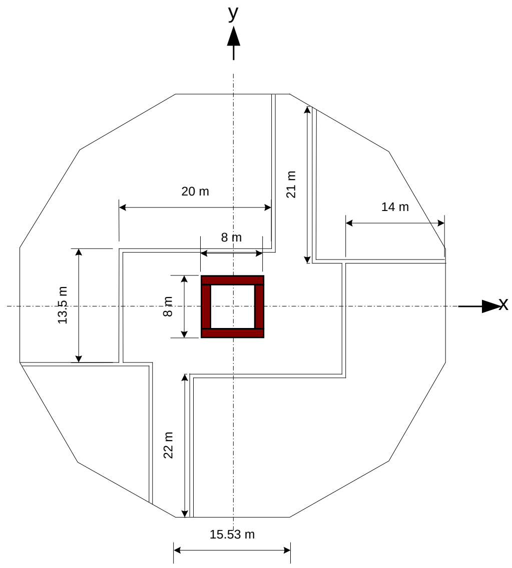


Figure 3 Plan view of dodecagon shape- equivalent to the Central configuration

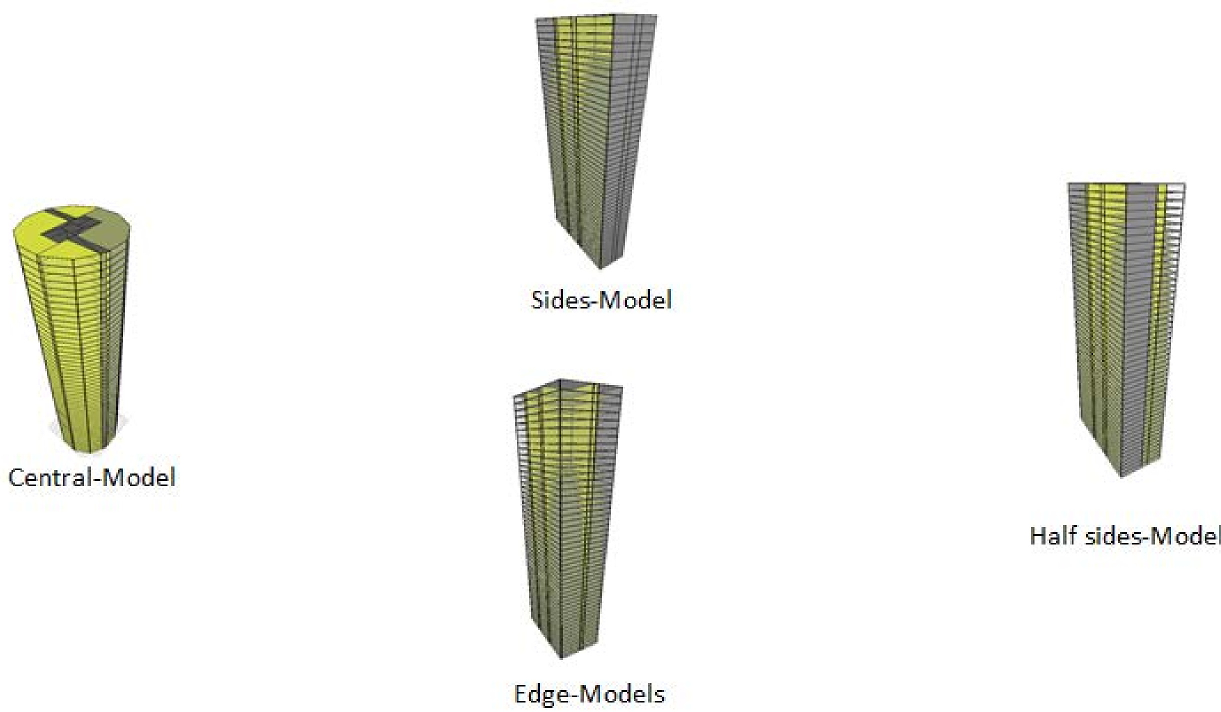


Figure 4 Ecotect 3D models

.

1.2.4. Thermal Analysis Result. The thermal analysis results are presented in tabular form to allow comparisons among the four buildings in the four climate zones. Table 4 provides the annual energy use for heating and cooling loads, energy use intensity, and the difference between Yeang's recommended configuration and the configuration that resulted in the lowest energy use intensity. Each row in Table 4 represents the results of examining each model configuration (Central, Edge, Half Sides, and Sides) in a climatic zone.

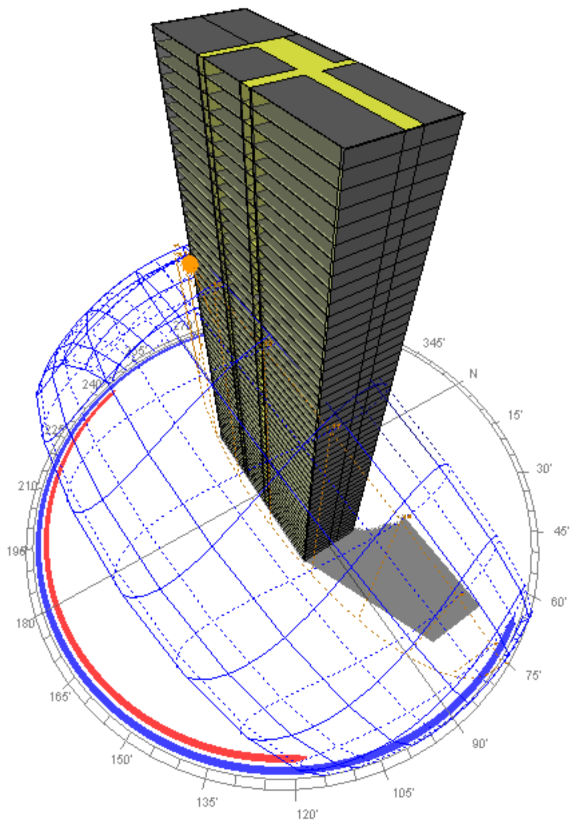


Figure 5 Sun-path diagram – building's walls shadow

The first row illustrates the thermal results in a cool climate. The annual energy loads for this climate are dominated by heating demand. This is an indication that the heating load should be viewed as a priority in optimizing energy efficiency rather than total heating and cooling demand. In our analysis, the Sides model resulted in the lowest EUI as well as heating demand. Yeang's recommended configuration is the Central model. The use of the Sides model in a cool climate might result in a reduction in energy consumption by 32% compared to Central, 16% compared to Half Sides model, and 9% compared to the Edge model. These differences are significant. The lowest ranking configuration – with the highest energy penalty– is Yeang's Central model.

The second row illustrates the thermal results in a temperate climate. According to the data obtained from the weather file this climate is dominated by cooling loads, which represent 68% of total annual degree-days (see Table 2). This is consistent with the results obtained from the thermal analysis, where the cooling load averaged 76.6 % for all four building configurations. The model that consumes the least amount of cooling energy is likely the most appropriate configuration for this climate. The Sides model has the lowest cooling load by a factor of 6.0 % compared with Yeang's recommended configuration (Edge), a difference that is very close to the percentage difference in annual total energy demand between the two models. The Edge model is the second ranking configuration, though the cooling load in the Half Sides model only differs by 0.96% compared with the Edge model (recommended configuration). The least favorable configuration is the Central model. The total energy demand of the Central model exceeds the Sides model by 19.9%, the Edge model by 12.9 %, and the Half-Side model by 8.2%.

The third row represents the thermal analysis results for an arid climate. The average breakdown of cooling and heating loads are 91.6% for cooling and 8.4% for heating. Nevertheless, in all cases, the cooling load is the higher percentage of the total energy need in this climate. The cooling energy demand is the lowest in the Sides model with a difference of 9% compared to Yeang's recommendation (Half Sides), which ranked third. The difference in EUI is 5% between the Edge model (second option) and Half Sides model (recommended model). The least favorable configuration for this climate is the Central model with higher energy consumption, exceeding the annual load for the Sides configuration by 17.4%.

The forth row represents the results of the thermal analysis in a tropical climate. Based on the weather data, the annual cooling degree-days represent 100% of the total degree-days (see table 2), which agrees with the results obtained from the thermal analysis. Also, the recommended model (Sides) is also the best option based on results from the thermal analysis. The differences in total energy consumption were 6% compared with the Central configuration, 5.7% compared with the Half Sides configuration, and 3.3% compared with the Edge configuration.

1.3. Structural Performance

Yeang does not refer to the impact of the distribution of structural cores (which he has defined to maximize energy performance) on the structural performance, and we note the existence of asymmetry in the floor plan in two configurations, Edge and Half Sides. Also, for the three symmetric models (Sides, Half Sides, and Edge) the walls provide the buildings with lateral resistance only in one direction; leaving the other direction too weak against any lateral load. Beyond that, from experience we believe that these lateral resistance systems will not be sufficient for skyscrapers. Therefore, it is obvious that additional lateral load resisting systems would be needed for these buildings. Nevertheless, in the following we investigate the structural performance of the structural cores as defined in Figure. 2.

Table 4 Annual heating and cooling loads

Type / Climate	Central			Edge			Half Sides			Sides			Yeang's recommended configuration	**% Difference** [between lowest EUI and recommended
	Heating (Mwh)	Cooling (Mwh)	EUI (kwh/m^2)	Heating (Mwh)	Cooling (Mwh)	EUI (kwh/m^2)	Heating (Mwh)	Cooling (Mwh)	EUI (kwh/m^2)	Heating (Mwh)	Cooling (Mwh)	EUI (kwh/m^2)		
Cool	7538	875	62.3	5992	877	51.4	6553	816	54.6	5548	777	46.9	Central	32%
Temperate	1310	3646	36.7	946	3443	32.5	1103	3476	33.9	884	3248	30.6	Edge	6.0%
Arid	990	7647	63.9	696	6904	56.3	841	7167	59.3	673	6677	54.4	Half Sides	9.0%
Tropical	0.0	7824	57.9	0.0	7612	56.4	0.0	7746	57.4	0.0	7372	54.6	Sides	0%

EUI: Energy Use Intensity

1.3.1. Building's Stiffness. Preliminary calculations are made to investigate the buildings' stiffness, and susceptibility to torsional deformation. Here, we consider that the structural walls act as cantilevers independently of each other except for in the Central modal where the walls are compose a square-tubular core. The bending stiffness of each independent structural component *i* of the lateral force resisting system is proportional to the product of the elastic modulus *E* and the cross section moment of inertia I_i of the shear wall. We denote the stiffnesses by k_i. The total bending stiffness of the lateral force resisting system K_{core}, then, is the sum of the *n* individual component stiffnesses (See Table 5 for the coordinate system considered) and is proportional to the sum of the products EI_i.

$$K_{core} = \sum_{i=1}^{n} k_i \propto \sum_{i=1}^{n} EI_i \tag{1}$$

where

E = assumed constant for all walls.

For a uniform wind load acting on a cantilever the lateral bending stiffness can be calculated as rigidity of the structural walls. The location of the center of rigidity from an arbitrary origin can be finding by using the flowing relationships:

(see table 5) and is significant in both cases. Higher eccentricity leads to higher twisting moment and requires higher torsional stiffness in the structural system. However, in the Sides and Central models we see no need for exceptional amounts of torsional stiffness beyond those needed to meet certain minimum code requirements, while in the case of the Edge and Half Sides models the design would be substantially affected by torsional effects, requiring additional stiffening and strengthening. Figure 6 shows a 3D view of how the different building types might deform under wind loads, where one mode of displacement (translation) occurs in the Sides and Central models, and two modes of displacement, translation and rotation, occur in the Half Sides and Edge models.

CONCLUSION

This paper examined four different building configurations, proposed in *The Green Skyscraper* (Yeang 1999), for lowering the energy consumption of skyscraper in four different climate regions. By simulating each building configuration using Autodesk's Ecotect, we were able to draw two major conclusions regarding building energy consumption:

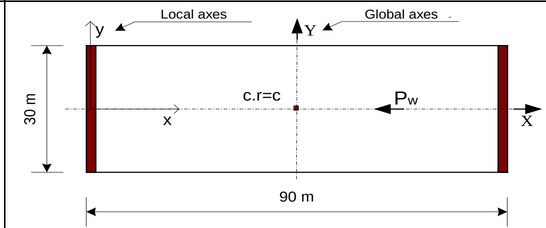
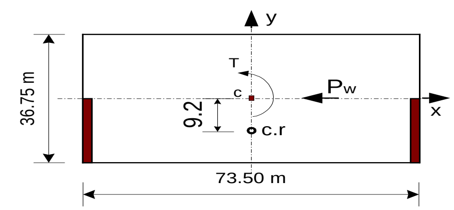
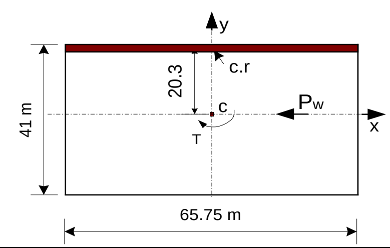
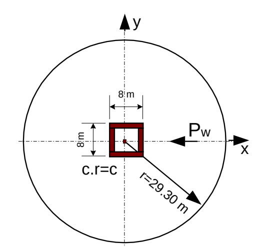
(1) The results prove Yeang's proposal that building configuration (footprint shape and the placement of structural vertical core/walls) significantly influences overall energy performance.

(2) The results demonstrated that the placement of the structural vertical core/walls in the east and west sides and with an aspect ratio of 1:3, may lead to a reduction in energy consumption of 6.0% to 32%, depending on climatic zone.

This paper provided an additional dimension to Yeang's thesis – we coupled the thermal analysis with an analysis of each configuration's structural stiffness. We found that for two of the proposed configurations, asymmetric distribution of the structural walls results in high torsion stress due to twisting. Moreover, asymmetry in the two configurations— called Edge and Half Sides models— generate a substantially eccentricity. We conclude that building configuration (footprint shape and the distribution of the structural core/wall) critically impacts the structural stiffness of a building.

Future research will focus on finding the optimal shape and core/wall placement for each of the four climate zones identified in this study. This will also include an investigation of the operational and embodied energy costs of increasing the thermal mass and core stiffness of skyscrapers.

Table 5 The models stiffness's and torsional susceptibility

Model	Cross section bending stiffness		Lateral stiffness		Torsional Stiffness	Torque	Torsional stress	Floor Plan
	x-axis	y-axis	x-axis	y-axis				
Sides	2025E	0.456E				0	0	
Half Sides	465E	0.279E				$9.2P_w$		
Edge	0.5E	10659E						
Central	129.7E	129.7E				0	0	

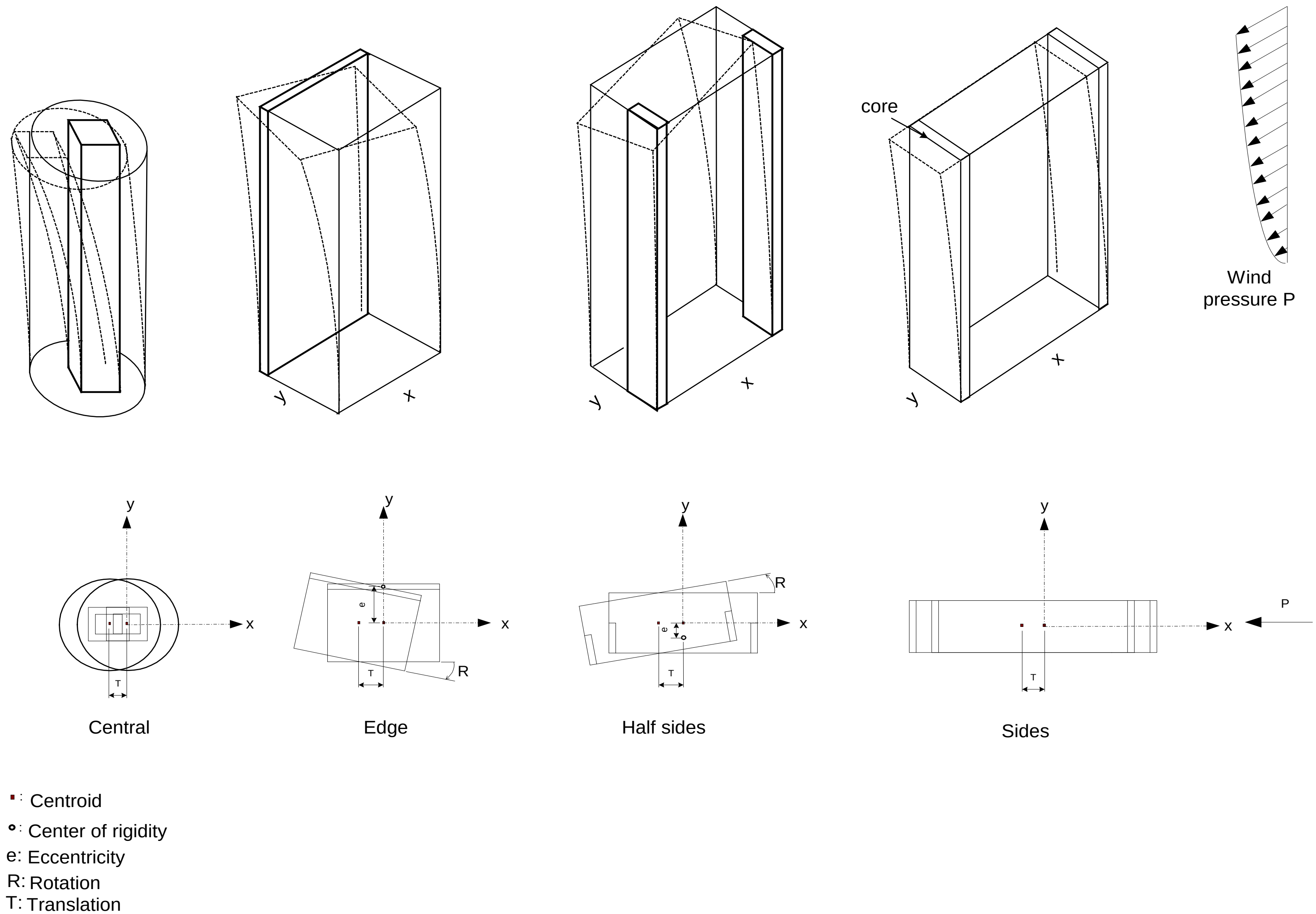


Figure 6 3D of how the different building types might deform under wind load

ACKNOWLEDGMENTS

This work was carried out at the University of Massachusetts Amherst (UMass). Special thanks go to the Environmental Engineering Department for providing me a full version of Ecotect 2011. Also, special thanks go to my financial supporter the Ministry of Education and Scientific Research in Tripoli, Libya. Lastly, I would like to thank Dr.Carl Fiocchi who helped me to figure out and understand some features of using Ecotect 2011.

References

Anderson, J., Silman, R. 2009. The role of the structural engineer in green Building. The Structural Engineer, 87:28-31.

Kestner, D., Goupil, J., Lorenz, E. (2010). Sustainability Guidelines for the Structural Engineer. Reston, Virginia.

Kottek, M., Grieser, J., Beck, C. (2006). World map of the Koppen-Geiger climate classification updated. Meteorologische Zeitschrift. 15:259-263.

Mak, C.M, Niu, J.L, Lee, C.T., Chan, K.F. 2007. A numerical simulation of wing walls using computational fluid dynamics. Energy and Buildings, 39:995-1002.

Popov,E.P. 1990. Engineering mechanics of solids. New Jersey: Prentice Hall

Straube, J. 2006. Green Building and Sustainability. Building Science Digest Press.

United States Green Building Council (2008). Green Building Research. <http://www.usgbc.org>.03 June 2009.

U.S. Department of Energy Building Energy Codes Program.2010. International Energy Conservation Code 2009. International code council, INC.

U.S. Department of energy, Energy plus.2011. <http://www.energy.gov/index.htm>.03 Jan. 2011

Webster, M.D. 2004. Relevance of structural engineers to sustainable design of buildings. Structural Engineering International. 14:181-185

Yeang, K. 1999. The Green Skyscraper. Prestel, Munich. London. New York.

Bibliography

ASHRAE standard .(2010). Energy standard for buildings except low-rise residential buildings. ASHRAE, Atlanta, GA.

Autodesk Education Community. (2011). < http://students.autodesk.com/?nd=home> (2011).

Bryan and Alex. (1991). Tall building structures: analysis and design. Wiley-Interscience Publication, John Wiley and song, INC.

Cheung, C., Fuller, R., Luther, M.(2004). Energy-efficient envelope design for high-rise apartments. Energy and Buildings. 37: 37–48.

Hasan Fathy.(1973). “Architecture for the poor.” University of Chicago Press.

Liu, L., Mak, C. (2007). The assessment of the performance of a wind catcher system using computational fluid dynamics. Building and Environment. 42:1135-1141.

Matthew Wells. (2005). Skyscrapers structure and design. Yale University Press.