Techniques of Sustainable and Green Skyscraper Design-Architecture Versus Structure Demands in Temperate climate

Mohamed Ali karim [1*], Muftah Mohamed A. sryh[2]

[1] omgaon2x@yahoo.com, [2] sryh@hotmail.com

[1] Civil Engineering, Engineering Faculty, Elmergib University, AL-khoms, Libya
*Corresponding author email: omgaon2x@yahoo.com

ABSTRACT

Tall structures and towers have captivated humans for thousands of years, and so they are a fact of modern life in cities for a variety of reasons. However, the most challenging design problem is meeting operational performance requirements and maintaining occupant comfort. Not only are the site energy costs high, the attendant environmental consequences of using non-renewable energy sources are great. This fact prompted searchers and designers to advance and fully embrace green and environmentally friendly design. One of the key goals of the green building movement and technique is to reduce the material, constructional, and operational costs of buildings. This goal can be accomplished by drawing on the synergies between building geometry, material usage, and the local climate demands. Architect Ken Yeang, in his famous book The Green Skyscraper, suggests that in different climate zones, they should be arranged in different locations to reduce the yearly energy consumption of the building. But Yeang's claim of the structural system 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. Thus, this study performs thermal and structural analysis to address the implications of different footprints and core placements on energy and structural performance. The results demonstrate that to accomplish Yeang's claim, a supplementary lateral load resistance system is needed, which demands additional

structural material. As a result, buildings with an asymmetric distribution of stiffness are the most expensive, which has a negative impact on the building's environmental and economic aspects.

Keywords: Sustainability, Green Skyscraper, Supplementary, Embodied Energy, structural System, Techniques

Introduction

Tall buildings and towers have fascinated humans for thousands of years. They were primarily built for defensive or religious purposes. Moreover, high-rise buildings have become a common feature of modern city life for a variety of reasons. Due to the scarcity of available land, the price of urban real estate, and the need to protect green space, a good solution to minimize traffic congestion in cities, the limitation of buildable land, due to the large concentration of government enterprises and commercials in city centers [1,2]. High-rise buildings pose a difficult design dilemma in terms of meeting operational performance requirements while retaining occupant comfort. Large-scale HVAC (Heating, Ventilation, and Air Conditioning) loads have considerable energy demands. Not only are site energy costs expensive, but the environmental ramifications of employing nonrenewable energy sources are also significant. Improving the energy efficiency of high-rise structures is a critical component of environmental sustainability. The construction and building industries are responsible for more than one-third of global energy usage [3]. There is a significant need to design and construct buildings that are more sustainable, given the dramatically rising energy consumption. Buildings that are energy efficient reduce resource consumption, operating expenses, and life cycle costs while also improving occupant health and comfort [4]. High-rise buildings should be designed in such a way that they use less fossil fuels (oil, gas, and coal) and rely more on passive/renewable energy. This philosophy is represented in what is today known as green building or sustainable design. A green building, in general, is one that serves current requirements while not jeopardizing future generations' ability to satisfy their own [1]. If a structure is designed with various environmental variables in mind, it may be able to take use of abundant solar or wind energy while minimizing its negative impact. This has the potential to reduce energy loads, resulting in lower CO2 emissions and a healthier and more sustainable building. Architect Ken Yeang argues in his famous book The Green Skyscraper that the structural core (structural wall) should be positioned in different positions in different temperature zones to reduce the building's yearly energy consumption (see figure 1) [1]. But, Yeung’s sustainable technique neglects that buildings with asymmetric distributions of stiffness are known to be sensitive to destructive torsional modes of vibration when subjected to wind or earthquake loading. Thus, this paper focuses on whether structural and energy performance considerations can be integrated and optimized concurrently. The second emphasis is on analyzing the tradeoffs in the design of structural systems for both structural and energy performance. The results demonstrate that a supplementary lateral load resistance system (SLLR) is needed, which demands additional structural material. This contradicts the principles of green building design and is environmentally and economically undesirable. Previous studies have shown the potential for structure to play a positive role in influencing the energy performance of buildings. For instance, Mak et al investigated the effect of wing walls on passive ventilation and found potential synergies between the structure and environmental performance [5]. Additionally, structural engineers have made substantive efforts to design sustainable structures. Anderson & Silman and Webster identify how the structural engineer may work with an integrated design team of architects, engineers, builders and owners to make the structure sustainable [6,7].

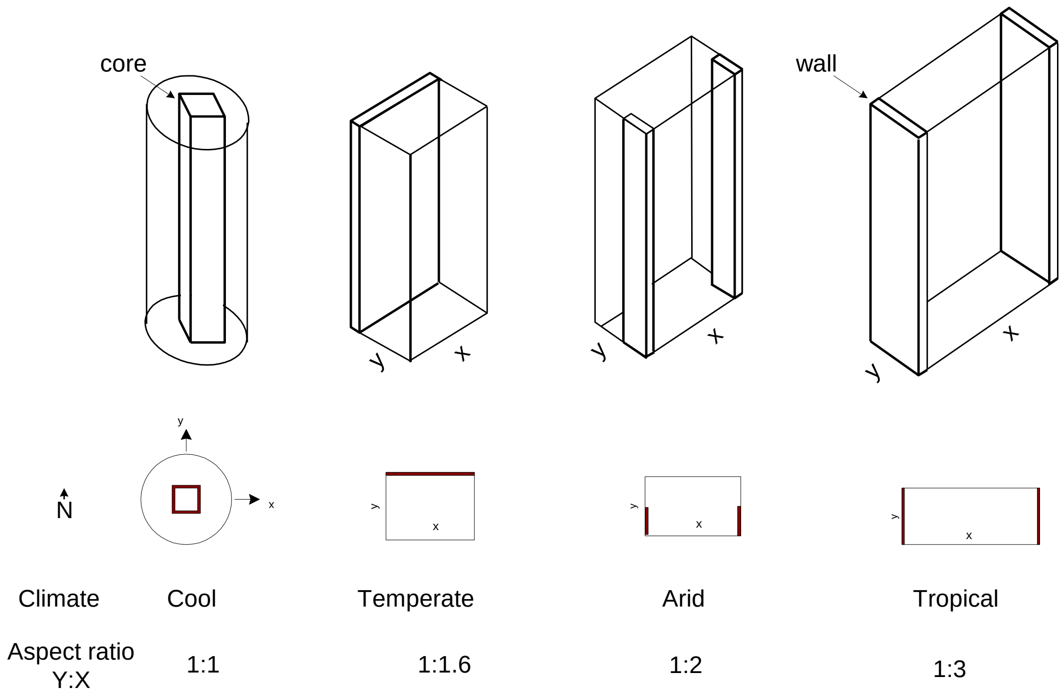


Figure 1. Proposal by K. Yeang for optimal floorplan and placement of structural core/walls to minimize building energy consumption in main four climate zones [1]

The Structural Engineering Institute of the American Society of Civil Engineers has recently published Sustainability Guidelines for the Structural Engineer, which emphasizes material selection and life cycle cost analysis as the basis for structural sustainability [8]. These publications promise to significantly affect the way that structural engineering is practiced, yet none directly address the interplay of structural form and energy efficiency, which is our primary interest. However, due to the large size of the subject of this study, it will deal in particular with the model of the temperate climate. The following sections demonstrate the method and the primary variables, then evaluate the results, and present the conclusion and the recommendations.

1. Problem Statement

To study Yeang's proposal, a model for high-rise office buildings was adopted, where the position of the vertical structural core/walls, as well as the aspect ratio and shape of the building footprint, are modified in this study, as they are in Yeang's, to optimize energy performance. All other morphological parameters for the modeled skyscraper are consistent, including square footage, number of stories, building height, occupancy, timetables, and envelope materials. All are 200 meters tall, with 50 stories ranging from 4.0 meters floor to floor and a total conditioned floor area of 135000 m^2. Figure 2 shows the model's plan views, as well as the locations of the primary mass (opaque surfaces) and the glazing walls (transparent surfaces) for each configuration. The structural core/wall (opaque walls) is made up mostly of reinforced normal weight concrete, while the glazed (curtain) walls are made up of two layers of conventional glass with a 10% metal frame. Ignoring the effect of nearby structures and building orientation to simplify the energy consumption analysis, and assuming that all buildings are placed on flat, open ground and aligned with the cardinal directions. The exterior envelope materials for all four models meet the 2009 International Energy Conservation Code, IECC [9]. And all four building morphologies are simulated in a temperate climate. Furthermore, the thermostat range, internal design conditions, occupancy, infiltration rate, and operating hours are all treated as fixed control variables as shown in Table 1.

2. The thermal Analysis (Energy Performance)

The proposed configurations based on where the structural core/walls are positioned (opaque walls) are described in the following sections: Central for cool zone; Edge for temperate zone; Half Sides for the arid zone; Sides for the tropical zone.

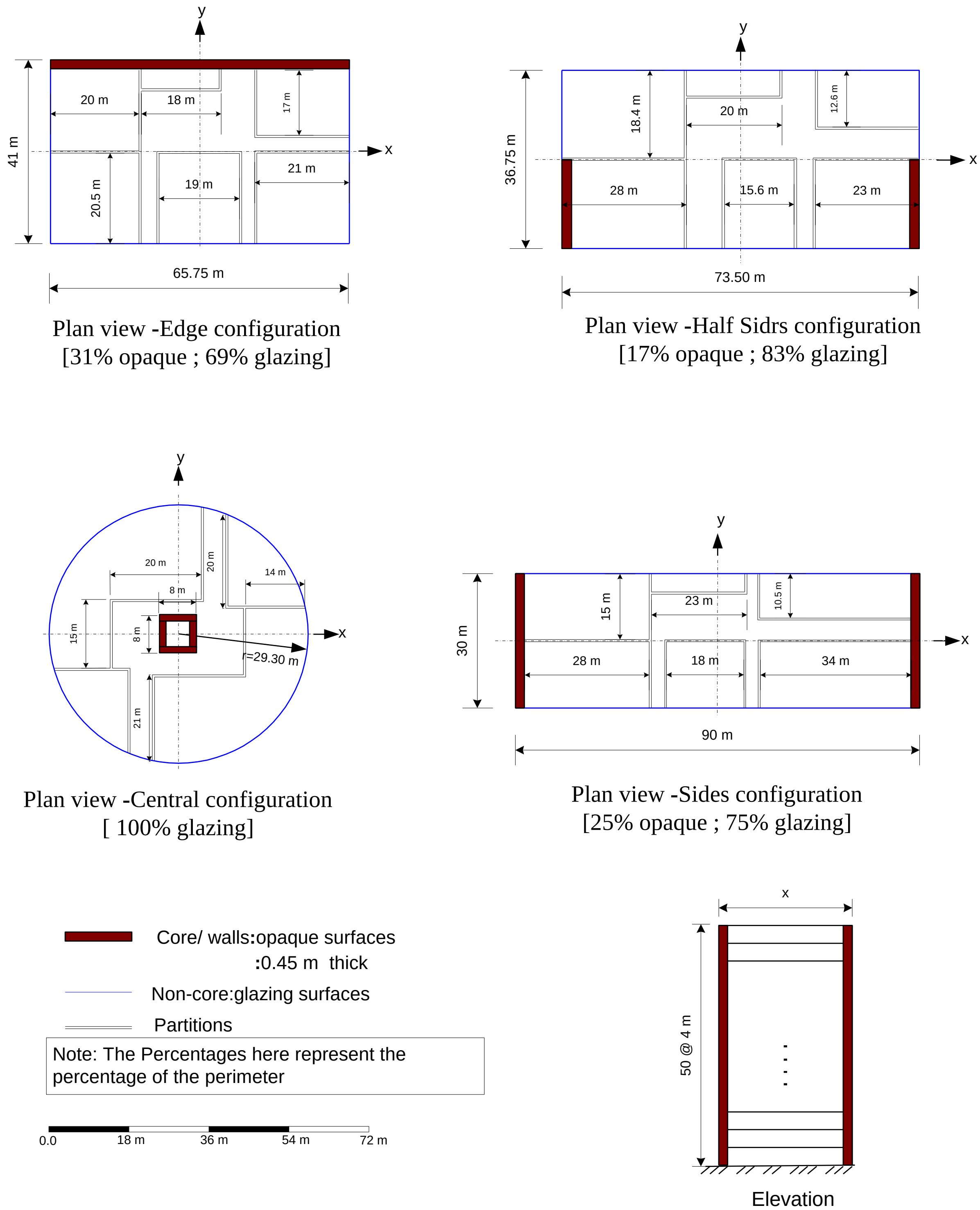


Figure 2. Plan views and an elevation of the buildings

Table 1. Thermal analysis conditions [9].

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*

2.1 Modelling.

For the thermal analysis, Autodesk's Ecotect 2011 energy simulation package was used. Ecotect 2011 is a full concept-to-detail sustainable building design tool; it is a popular program used by engineering since the modeling technique is straightforward, the properties of models can be quickly changed, and large models can be analyzed in a fair amount of time. Briefly, the Ecotect approach begins with the creation of a three-dimensional shell that represents the building form. Create a 3D model by drawing plans that describe the room boundaries, continuing room by room to form a 3D model. Thermal parameters are assigned to the building's envelope after the import, and the analysis may begin. The fundamental material of an element (concrete wall, slab, glass wall, etc.) is allocated, and then the insulation resistance (R-value) is applied, according to IECC code. The next stage is to assign the weather data file that matches to the study's climatic zone (temperate climate), as well as offer occupancy and scheduled usage statistics. Finally, the computer can estimate monthly and annual heating and cooling loads based on occupancy and scheduled usage data, and the given climate conditions.

2.2 Thermal Analysis

Each of the four models (Central, Edge, Half Sides, and Sides) is examined in a temperate climate for the thermal analysis (cool, temperate, arid, and tropical). The four models are tested under the same parameters of thermal characteristics and weather data [10]. That is, the aspect ratio and placement of the structural cores/walls are the only variances amongst the four runs in the same climate zone. Ecotect evaluates the impact of solar insolation on each building's heating and cooling requirements. However, as an example, Figure 3 shows a sun-path diagram and how the building's side walls shading the building on the east and west sides in this instance.

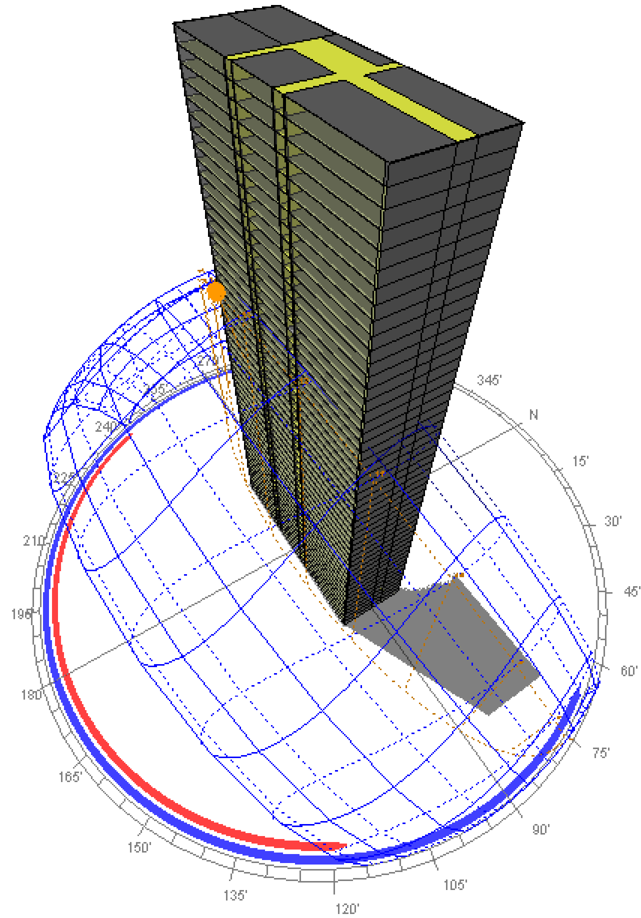


Figure 3. Sun-path diagram – building's walls shadow as it in the model run

2.3 Thermal Analysis Result

The findings of the thermal analysis are tabulated to allow comparisons between the four buildings in the selected climate zone. The annual energy usage for heating and cooling loads, energy use intensity, and the difference between Yeang's recommended design and the configuration that resulted in the lowest energy consumption are all shown in Table 2. The thermal results in a temperate climate are dominated by cooling loads, which revealed that the cooling load for all four-building configurations averaged 76.6 percent. For this environment, the model that uses the least amount of cooling energy is most likely the best option. This is especially true of the Sides model. The Edge model (Yeang's recommended configuration) is the second-best configuration, despite the fact that the cooling load in the Half-Sides model is only 0.18 percent lower. The Central model is the least desirable; it consumes 19.9% more energy than the Sides model, 12.9% more than the Edge model, and 8.25% more than the Half-Sides model. Returning to the best option in a temperate climate, the Sides configuration is 6.2% better than the Edge configuration recommended by Yeang.

3. Investigate the Structural Performance

Considering the vertical core/walls are the only portions of the structural system that are found to resist lateral loads, as shown in Figure 2, they were arranged in this way to reduce energy consumption (Yeang recommended). It can be seen that there is an occurrence of asymmetry in the floor plan in two configurations, the Edge and the Half Sides. Yeang does not allude to the influence of these distributions on structural performance. Furthermore, the walls of the three prismatic models (Sides, Half Sides, and Edge) only give lateral resistance in one direction, leaving the other direction too weak to withstand any lateral load. Beyond that, one can feel that these lateral resistance devices will not be sufficient for skyscrapers based on previous experience. As a result, it is clear that these structures will require extra lateral resistance systems. In other words, the current lateral resistance systems are unrealistic and will not be suitable for these high-rise structures.

Table 2. Annual heating and cooling loads

Configuration Type	Energy Demand	Temperate climate			Yeang's recommended configuration for Temperate climate	Difference between lowest EUI and recommended configuration (%)	The Extreme Difference (%)
		Load	∑	%			
Central	Heating (Mwh)	*1310*	*4956*	*26.4*	Edge	6.2%	19.9%
	Cooling (Mwh)	*3646*		*73.6*			
	Energy Use Intensity (kwh/m^2)	*36.7*					
Edge	Heating (Mwh)	*946*	*4389*	*21.6*			
	Cooling (Mwh)	*3443*		*78.4*			
	Energy Use Intensity (kwh/m^2)	*32.5*					
Half Sides	Heating (Mwh)	*1103*	*4578*	*24.1*			
	Cooling (Mwh)	*3476*		*75.9*			
	Energy Use Intensity (kwh/m^2)	*33.9*					
Sides	Heating (Mwh)	*884*	*4132*	*21.4*			
	Cooling (Mwh)	*3248*		*78.6*			
	Energy Use Intensity (kwh/m^2)	*30.6*					

% means the percentage of a load (heating or cooling) from the total load; ∑ the summation of Heating and cooling

3.1 Building's Stiffness

As previously stated, preliminary calculations are performed to evaluate structure attributes such as stiffness and torsional susceptibility using the specified lateral resistance systems. Consider the structural walls as cantilevers that move independently of one another, with the exception of the central modal, where the walls are made up of a square core. The flowing relationship is used to calculate the bending stiffness of a wall's cross section around the local axis:

$$Cross\ section\ bending\ stiffness = \sum_{1}^{n} E\,I \qquad (1)$$

where

E = the modulus of elasticity

I = the area moment of Inertia

n= number of the walls

The lateral bending stiffness of a contriver under a uniform wind force can be determined as follows:

$$k = \frac{8EI}{h^4} \qquad (2)$$

where

h= the height of the structural wall

The torsional stiffness of the structural wall as flowing is calculated using the concept of torsional stiffness for solid noncircular members:

$$k_t = \frac{bt^3G}{3h} \qquad (3)$$

where

G= the modulus of elasticity in shear

b= the length of the long side

t = the width of the short side

An asymmetry in plan about the loading axis would cause eccentricity, which would result in twisting as well as translating, resulting in a combination of translation and rotational floor displacement. The eccentricity here refers to the perpendicular distance between the floor centroid and the structural wall's center of rigidity. Flowing relationships can be used to discover the location of the center of stiffness from any arbitrary origin:

$$\bar{x} = \frac{\sum EIx}{\sum EI} \quad (4)$$

$$\bar{y} = \frac{\sum EIy}{\sum EI} \quad (5)$$

where

EI_x and EI = respectively, the sum of flexural rigidities and the sum of the first moments of the flexural rigidities about the origin, for all the walls parallel to the Y axis.

EI_y and EI = respectively, the sum of flexural rigidities and the sum of the first moments of the flexural rigidities about the origin, for all the walls parallel to the x axis.

Exacting an eccentricity in the floor plan generates irregularity in the rigidity, producing in torsional stress, which is estimated as flowing:

$$\tau = \frac{T}{3bt^2} \quad (6)$$

Where

T= is the twisting moment per unit height acting about a vertical axis of the building.

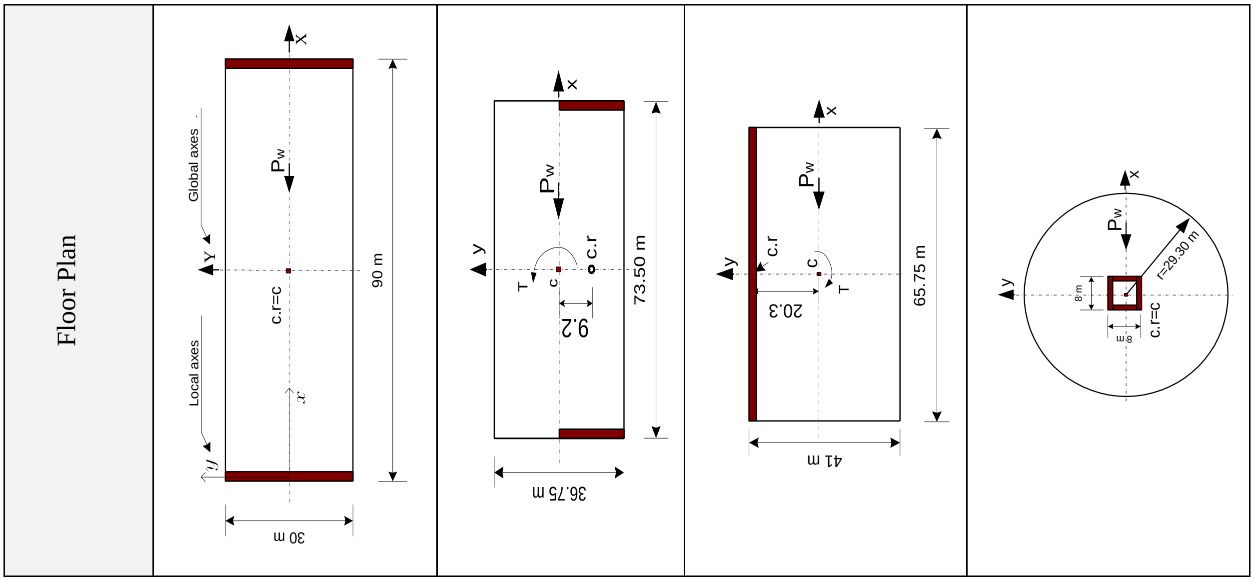
This twisting moment resulting of the eccentricity (e), which is the perpendicular distance between direction of the wind load P_w (floor centroid) and the center of rigidity (c.r) of the shear walls in floor plan.

$$T = e \times P_w \quad (7)$$

3.2.1 Structural Performance Results

Table 5 shows the results of calculating stiffness and torsional susceptibility, with the Sides model having the highest cross section bending stiffness about the local x-axis, the Half Sides model second, the Central model third, and the Edge model having the lowest stiffness about this axis. The Edge model, on the other hand, has the largest cross section bending stiffness around the local y-axis, while the Half Sides and Sides models are quite weak about this axis, while the Central model maintains the same stiffness due to symmetry. Because lateral stiffness is determined by the area moment of inertia, the lateral stiffness of a building exhibits the same behavior as cross section bending stiffness. As previously stated, asymmetry on a plan about the loading axis causes eccentricity, which most likely results in two modes of displacement occurring at the same time (translation and rotation). This eccentricity exists in two models (see table 3) with a very high magnitude of eccentricity; higher eccentricity results in a higher twisting moment and demands a higher torsional stiffness. However, can see no need for torsional stiffness in the Sides and Central models unless to meet certain minimum requirements according to a code, whereas torsional stresses would significantly affect the design in the Edge and Half Sides models, where the torsional stress in the Half Sides is 1.64Pw and 0.51Pw in the Edge model. Figure 4 depicts in three dimensions how different building types might deform under wind loads, with one mode of displacement (translation) in the Sides and Central models and two modes of displacement (translation and rotation) in the Half Sides and Edge models. It is clear that the shape of the building and the distribution of the structural core/wall will have a significant impact on the stiffness and substantially of the structure.

4. Conclusion



This research looked at four potential building configurations for minimizing skyscraper energy consumption; in the context of optimizing the structural system of a building to improve energy efficiency in addition to resisting gravity and lateral loads. The thermal study results demonstrate that the built-form configuration (footprint shape and placements of structural vertical core/walls) in the skyscraper's perimeter has a major impact on energy performance, as mentioned by Yeang in his book.

Table 3. The models stiffness's and torsional susceptibility

Model	Cross section Bending Stiffness		Lateral stiffness		Torsional Stiffness	Torque	Torsional Stress
	x-axis	y-axis	x-axis	y-axis			
Sides	2025E	0.456E	16200E/h^4	0.135E/h^4	1.82G/h	0	0
Half Sides	465E	0.279E	465E/h^4	0.083E/h^4	1.12G/h	$9.2P_w$	$1.64P_w$
Edge	0.499E	10659E	0.5E/h^4	10659E/h^4	2G/h	20.3P_w	0.51P_w
Central	129.7E	129.7E	1037E/h^4	1037E/h^4	G/h	0	0

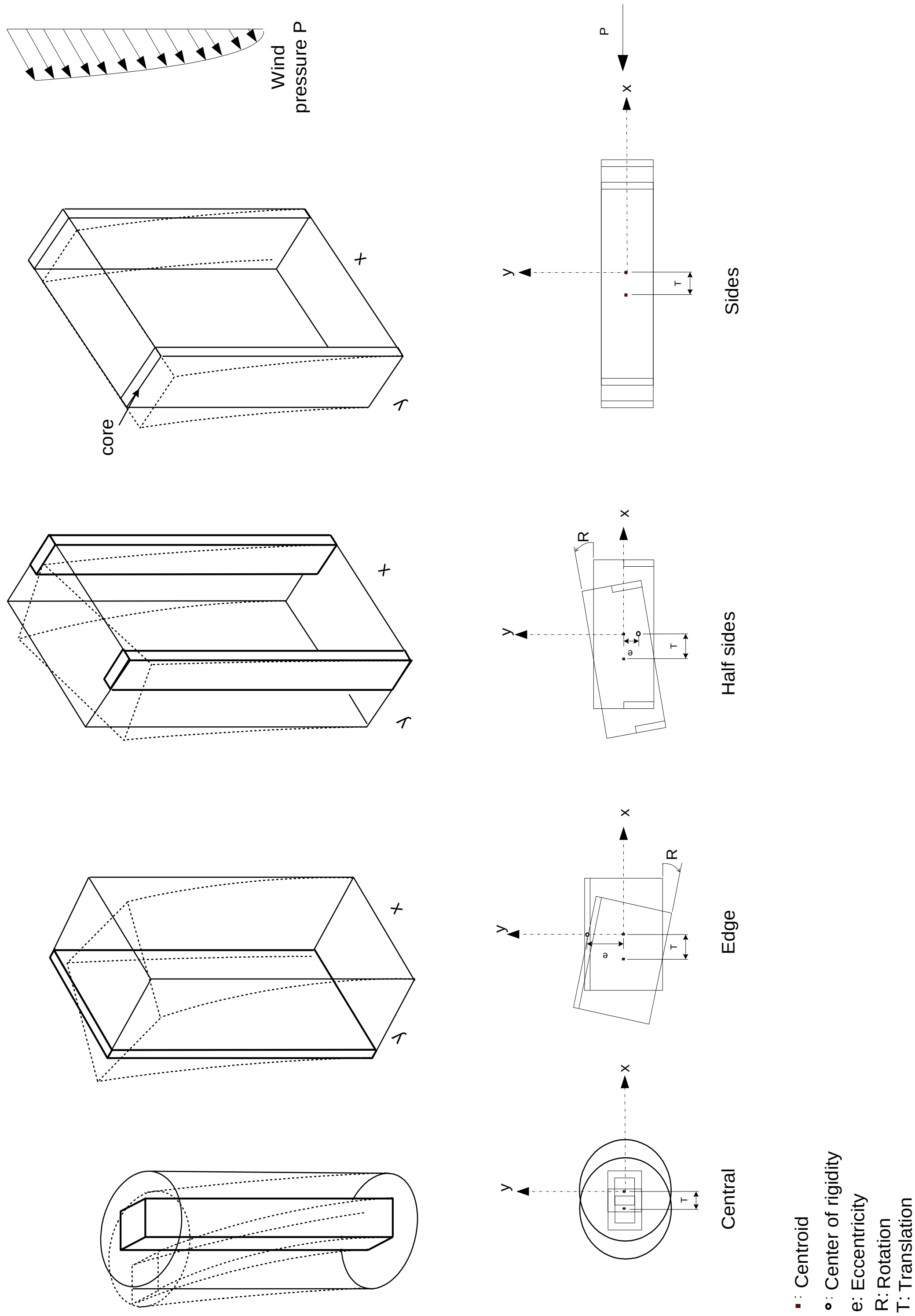


Figure 4. 3D of how the different building types might deform under wind load

Furthermore, the findings reveal that, depending on the temperate climate zone, placing the structural vertical core/walls on the east and west sides with an aspect ratio of 1:3 may result in a 5 % to 20% reduction in energy consumption. However, the asymmetric distribution of structural walls may result in excessive torsion stress owing to twisting, making an asymmetric skyscraper more expensive than a symmetric skyscraper. Also, asymmetry in the two models—the Edge and Half Sides models—creates a significant amount of eccentricity, leading to large torsional stresses in both configurations. In addition, Yeang also recommends varied wall distributions for Sides, Half Sides, and Edge. Only one direction has bending and torsional stiffnesses, while the other direction has nearly no stiffnesses. Therefore, this imposes the presence of an additional system as a supplementary lateral load resistance system, which leads to an increase in the quantity of construction materials needed for the supplementary system. This leads to an increase in the cost of the building, so the corresponding energy savings lead to higher embodied energy. Finally, from an architectural standpoint, the notion of attaining sustainability in high-rise structures by making best use of what nature gives or by taking advantage of the geometry characteristics of high-rise buildings must not compromise the structural system's requirements. Nor will the results be uneconomic and unsustainable. Nevertheless, based on this conclusion, positioning the opaque surfaces on the East-West sides significantly improves energy performance for two building configurations (the Sides and the Central), and also the placement of these opaque surfaces made for the structural purposes is highly desirable (to reduce torsional displacement under lateral loading) .Thus, the first recommendation would focus on optimizing each of these configurations (the Sides, the Central) for the temperate climate zone. This optimizing should consider energy and structural performances, trade-off between the cost of the high-performance envelope versus the increased the energy performance. The second recommendation would be to find out how the structural performance of these two configurations would change, if the building height is increased and how this affects the total cost (energy and material) for a given building life span. Third recommendation would be to include a finance comparison between use insulation material and use of thermal mass of the structural system, which inherently have a good characteristic of thermal insulation; taking into account the embodied energy for both the insulation and thermal mass materials. Lastly, investigate how the energy demand would change if the system type is Mixed-Mode System (rather than a full Air-conditioning system), which is a combination of air-conditioning and natural ventilation. This investigation may require changes in the building morphologies for natural ventilation; the latter may possibly affect the building structural performance.

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