Concepts in the Design of Lateral-Load Systems in High Rise Buildings to Reduce Operational Energy Consumption

Mohamed A.M.K. Salem[1], Sergio F.Breña[2] , Sanjay R. Arwade[3], Simi T. Hoque[4] , and Nurdeen M. Altwair[5]

Abstract— The location of the main lateral-load resisting system in high-rise buildings may have positive impacts on sustainability through a reduction in operational energy consumption, and this paper describes an assessment of the accompanying effects on structural performance. It is found that there is a strong influence of design for environmental performance on the structural performance the building, and that systems selected primarily with an eye towards energy use reduction may require substantial additional structural stiffening to meet safety and serviceability limits under lateral load cases. We present a framework for incorporating the environmental costs of meeting structural design requirements through the embodied energy of the core structural materials and also address the issue of economic cost brought on by incorporation of environmental concerns into the selection of the structural system. We address these issues through four case study high-rise buildings with differing structural morphologies (floor plan and core arrangement) and assess each of these building models for cost when the base structural system, which has been suggested by architect Kenneth Yeang based on environmental concerns, is augmented to meet lateral drift requirements under the wind loads prescribed by ASCE 7-10.

Keywords— Efficiency, Morphology, Outrigger, Skyscraper, Sustainable

I. Introduction

IMPROVING the energy efficiency of medium to high-rise buildings is a key component in increasing the sustainability of the built environment. This is being pursued by so-called passive design strategies, an approach to building design that uses the building architecture to minimize energy consumption and improve thermal comfort. Given the current global energy crisis, there is a critical need to design and construct buildings that are more sustainable. Due to increasing urbanization high-rise buildings in particular should be designed in a manner to reduce energy consumption and the associated carbon footprint.

Mohamed A.M. Salem is the executive director of research and Consultation Center, and he is faculty member in the Department of Civil Engineering University of Al-Mergeb, Khoms Libya, (phone: 00218-91-318 3919; email: omgaon2x@yahoo.com)

Sergio F. Breña , is an associate Professor, Civil and Environmental Engineering, UMass-Amherst, MA, US (email: brena@ecs.umass.edu).

Sanjay R. Arwade, Associate Professor, Civil and Environmental Engineering, UMass-Amherst, MA, US (email: arwade@umass.edu).

Simi T. Hoque, Assistant Professor, Department of Environmental Conservation, UMass-Amherst, MA, US (email: simih@eco.umass.edu).

Nurdeen Altwair is faculty member in the Department of Civil Engineering University of Al-Mergeb, Khoms Libya, (phone: 00218-92-725-3938; email: nurdeenaltwair@gmail.com).

The structural engineering profession has been, in recent years, attempting to define the proper role for the structural engineer in the pursuit of sustainability of the built environment. Anderson and 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 a structure sustainable [1], [2]. The Structural Engineering Institute of the American Society of Civil Engineers recently published *Sustainability Guidelines for the Structural Engineer*, describing approaches to structural sustainability for the structural designer [3].

In his book *The Green Skyscraper* , architect Kenneth Yeang suggests that in different climate zones the structural core/wall system should be positioned to reduce the yearly energy consumption of the building. Furthermore, he argues that the shape of the building should be based on the climate zone in which the building is to be constructed (see Fig. 1) [4]. These parameters (which we call the building morphology) have clear implications for the 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 loads [5]. The potential interaction between structural and environmental performance of different structural systems has not yet, however, been examined.

In terms of energy performance, a study to investigate Yeang's proposals has been made by the current authors that showed that the choice of building morphology may lead to a differences in energy consumption of between 6% and 32%, depending on the climate zone [6]. In the present paper results from structural analyses are presented to determine if the structural system morphology proposed solely on the basis of energy efficiency is adequate to safely support structural actions such as wind loading in accordance with ASCE 7-10 [7].

Preliminary structural analyses have been carried out to determine at what height these given base structural systems (BSS) can meet the wind load lateral drift serviceability requirement as defined by ASCE 7-10. Furthermore, a conceptual design was carried to determine a supplemental lateral load resisting (SLLR) system that is needed to augment the BSS beyond certain height limitations. The economic and environmental costs of the SLLR must be considered in any holistic evaluation of building environmental performance.

The focus of this paper is twofold: (1) to define the SLLR system needed to resist gravity and lateral wind loads; (2) to evaluate the added cost to the building of including the SLLR system.. These two steps represent a step towards a fully integrated framework for combined structural and environmental assessment and design of the structural systems of mid- to high-rise buildings.

SAP2000 is used to perform 3D structural analysis for each of the four buildings, while hand calculations are provided to estimate cost.

The shear walls in mid- to high-rise buildings, which here form the BSS, respond as cantilevers, and the design of high-rise buildings is frequently controlled by the lateral displacement which is resisted by those shear walls. We thus consider the lateral displacement as a primary factor of this study. We propose to use an outrigger-braced system, which usually consists of a stiff core, connected to edge columns, where under lateral loading, the outriggers stiffen the core against overturning, generating tension in the windward columns and compression in the leeward columns [5].

Furthermore, the outrigger-braced system is an efficient system that increases building stiffness and has therefore been widely used in tall building structures [8] The core of the system consists of concrete shear walls (BSS) that are supplemented by an SLLR composed of a steel braced frame. We will also focus on the effect of structural material choice on cost. The selected buildings have equal height, equal number of stories, and the same square footage.

Previous studies have shown the potential for structure to play a positive role in influencing the energy performance of buildings. Cheung et al. (2004) showed that designing the building envelope according to local climate demands could lead to better control of interior building temperatures and hence help reduce building energy consumption. This study demonstrated that using these passive strategies can save up to 31.4% of annual required cooling energy [9].

In the following sections we define the selected modeling variables for structural analysis so as to evaluate the interplay between structure and energy performance. We then present the results of structural calculations and cost estimates for each scenario, and finally discuss results on the basis of lateral drift under wind load, building cost based on material used.

II. Description Of Building Models Variables

In this paper we name the candidate building morphologies according to the location of the structural cores that form the BSS. These configurations are: Central; Edge; Half Sides; and Sides (see Fig. 1). Other building descriptors, such as square footage, number of stories, and building height, were reasonably assumed for a high-rise office building. All are 50-story, 200 m tall buildings with a 4.0 m inter-story height.

There are three main structural systems in each building: 1) the base structural system core/walls (BSS) for lateral loads; 2) Non-moment steel frame for gravity loads; and 3) steel braced frame for added lateral load resistance (SLLR). The BSS consists of the core as proposed by Yeang [4], on the basis of sustainability considerations. Structural walls are assumed to be constructed using normal-weight reinforced concrete with a compressive strength of 28 MPa (4 ksi). Note that this assumed compressive strength is not representative of all high-rise construction but the material selected is to illustrate the concepts in this paper and the results would not be expected to change qualitatively if a higher strength concrete were assumed. Based on the assumed concrete strength and on the preliminary calculations of flexural strength for shear walls, the wall thickness increases from 0.60 m at the top, to 0.7 m at the thirty-seventh floor, 0.8 m at the twenty-fifth floor, and 0.9 m below the twelfth floor. The common assumption of including cracking in reinforced concrete walls by decreasing the gross moment of inertia (Ig) to Icr= 0.5 Ig was used. The SLLR system consists of a braced frame connecting the core to edge columns using an outrigger system at three levels: one quarter, one half, and the three quarters of the total building height [5]. The gravity system and SLLR are constructed using steel W-shapes and built-up sections satisfying ASTM A992 Grade 50 steel (IS, Grade 420).

The fundamental periods of the proposed buildings (used in calculating wind loads) were initially estimated using the common approximation of T = 0.1N [5], where N is the total number of stories. For the subject buildings, then, T = 0.1 × 50 = 5.0 sec (f = 0.2 Hz). Since the approximate fundamental frequency (f) is considerably less than 1 Hz these buildings are considered flexible structures in accordance with the commentary section 26.2 of ASCE 7-10.

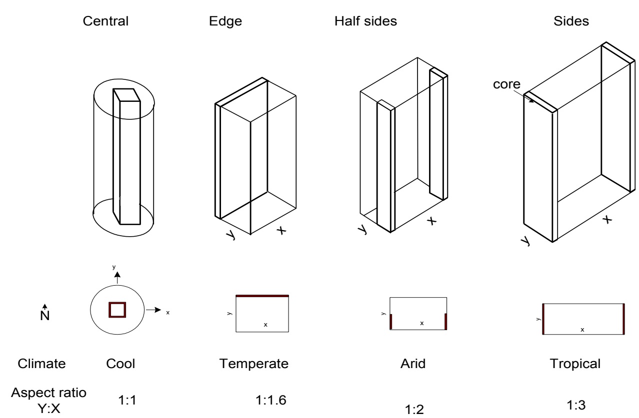

Fig. 1 Proposal by K. Yeang for optimal floor plan and placement of structural cores to minimize building energy consumption in four climate zones[4]

III. Building Model Loading

Gravity loads consist of dead and live loads, where the assumed dead load is 2.52 kN/m^2 (52.6 Ib/Ft^2) including the floor decking, allowance for floor beam weights, and allowance for superimposed dead loads; the live load used was 3.12 kN/m^2 (65.2 Ib/Ft^2) including live load and a partition allowance. Lateral load resulting from wind pressures was calculated according to the directional procedure in ASCE 7-10. For application of this procedure, the assumed wind load characteristics are: basic wind speed of 58 m/s (130 mi/h) (Boston region); exposure category B (urban terrain); building classification category II; gust effect factor G= 0.92; wind directionality factor Kd =0.85.

Typically, lateral displacements of concern in serviceability from the effects of wind are on the order of 1/600 to 1/400 of

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the building height (ASCE 7-10). For the subject buildings, then, with a 200 m height, the serviceability threshold for lateral displacement under wind is 0.5 m (1.64 Ft). Two wind load cases were considered: Case 1 corresponding to full design wind pressure acting on the projected area perpendicular to each principal axis of the structure, considered separately along each principal building axis; and Case 2, three quarters of the design wind pressure acting on the projected area perpendicular to each principal axis of the structure, considered separately for each principal axis. The purpose of load Case 2 is to induce building torsion even in the case where the structural system is doubly symmetric.

IV. Base Structural System

For the purpose of reducing the operational energy consumption, Yeang [4] recommended for each building configuration a position for the core and structural walls. These configurations result in basic structural systems (BSS) that are defined primarily to improve the energy performance of the building. Buildings with asymmetric distribution of stiffness, however, are known to be susceptible to damaging torsional modes of vibration when subjected to lateral load. We note this asymmetry in the floor plan in two configurations as defined by Yeang, the Edge and the Half Sides configurations. Also, in three configurations (Sides, Half Sides, and Edge configurations), the walls provide lateral load resistance in only one direction of the buildings, while in the perpendicular direction the core wall system provides little or no lateral load resistance. These observations illustrate the potential risks in specifying a lateral load resisting system based on energy performance without paying adequate attention to the structural implications.

In order to evaluate the lateral displacements in the BSS under realistic wind load conditions, 3D analysis using SAP2000 was performed. The BSS displacement behavior for the four proposed configurations was used as a guide for a more appropriate structural design. As we mentioned, the gravity system consists of non-moment steel frames (beams and columns), while the BSS is formed by normal weight concrete shear walls. The boundary conditions at the base are assumed as fixed supports for shear walls, pin supports for the steel gravity columns, and pinned beams ends. The BSS is the only system considered to resist the lateral loading.

Results of the analyses of the buildings under Case 1 wind loading show that the lateral displacements at the building top exceed the serviceability limit of 0.5 m (see table I). Torsional displacement was observed in the Half Sides and Edge models due to their asymmetric distribution of stiffness. The displacement is high in y direction (Uy) in the Sides model when the building is subjected to y-direction wind loading (Pwy) although the highest wall stiffnesses in oriented parallel to this direction. This is due to the larger exposed area for this direction of wind loading that leads to high wind forces. These results indicate that the size and number of shear walls in the Sides model are not adequate, even though they fully cover both east and west sides

Similarly, the Half Sides model exhibits a large y-displacement (Uy) when subjected to y-direction loading, indicating that the BSS shear walls do not provide adequate stiffness to meet the serviceability requirements. The BSS of the Sides and Half Sides models have negligible stiffness in the x-direction and the buildings exceed drift limits.

In the Edge model, on the other hand, the BSS shear wall provides stiffness only in the x direction and due to its location on only one side causes a severe stiffness asymmetry. The stiffness eccentricity, defined as the perpendicular distance between the floor centroid and the center of the rigidity of the structure leads to combined translation and twisting of each floor. The lack of building stiffness in the y direction and the large stiffness eccentricity leads to the large displacements that greatly exceed the serviceability limit.

In summary, the analysis with wind load Case 1 resulted in displacements that are beyond the serviceability limit in all models. For this reason the models were not analyzed under Case2 loading since the buildings are already in violation of code-prescribed limits for Case1. The results show that the wall distributions for Sides, Half Sides, and Edge models provide stiffness only in one direction while the structural system is too flexible in the orthogonal direction. Clearly, although these systems may in some sense be optimized for environmental performance, they must be supplemented to meet structural requirements. Asymmetry in the Edge model generates substantial eccentricity, causing a large torsional displacement mode. The core in the Central model does not have adequate stiffness in either direction to meet the serviceability limit. Therefore, the four building types need SLLR to resist ASCE 7-10 wind loading for a building height of 200 m.

The approach will be to increase the effective structural depth by connecting the core to the edge columns. The selection of the SSLR system was based in part on ensuring that similar SLLR could be applied for all of the building types, so focus could instead be placed on determining the additional material needed for the SSLR needed beyond that used in the base structure.

TABLE I
LATERAL DISPLACEMENTS RESULT OF BSS MODELS

	Displacement due to wind pressure P_{wx} Ux (m)	Displacement due to wind pressure P_{wy} Uy (m)	Serviceability limit (m) (ASCE 7-10)
Sides	1.55	1.1	
Half Sides	2.1	2.16	0.5
Edge	1.8*	4.0	
Central	1.33	2.1	

* Deformation due to torsional displacement.

V. Supplementary Lateral Load Resistance

An outrigger system was chosen then as SLLR to control drift of each building and reduce the bending demand in the core. Outrigger systems are economical and efficient lateral load systems, because the system utilizes the axial strength and stiffness of the perimeter columns to resist overturning by increasing the lever arm at different heights along the structure.

Taranath illustrates that outrigger structures are commonly used in buildings up to 70 stories[5]; Smith and Coull illustrate that structures braced using outriggers have been successfully used in buildings from 40 to 70 stories, and they believe the system is efficient for much greater heights [8].

In this paper, we use steel truss outriggers to reduce the lateral displacement; the outriggers are located at three floor locations, which could also serve as mechanical floors, namely floors 12–13, 25–26 and 37–38. Additionally, the exterior columns at each of these floor levels are connected using a truss perpendicular to the outrigger plane so as to engage a greater number of exterior columns in the outrigger action and better distribute axial forces. Connecting to interior columns reduces the outrigger span, and creates a stiffer 1-story outrigger.

All of the modified buildings are analyzed for two wind load cases (Case1 and Case2). Case2 takes into account the presence of eccentricities ex and ey measured in the x and y axes of each structure, respectively. Stiffness eccentricity was calculated using equation 27.4-5 in ASCE 7-10. Computed eccentricities in the x and y directions corresponding to each configuration are listed in Table II.

The SLLR, when sized according to the strength design load combinations in ASCE 7-10 does not meet serviceability requirements on lateral drift (Table II). The SLLR was therefore sized to provide adequate lateral stiffness and limit the drift to that prescribed by ASCE 7-10, namely 0.5 m.

VI. Displacement Results Including

SLLR improved buildings stiffness to resist lateral displacements and allowed all buildings to meet the serviceability limit. Table II illustrates the lateral displacements at the roof of the buildings. In the case of the Sides configuration the lateral displacement resulting from loading Case 1 governed the response. The differences in maximum displacements from loading Case 2 are 7% and 25% for Ux and Uy, respectively. In the case of the Half Sides model, loading Case 2 results in a higher lateral displacement than Case 1, with Uy equal to 0.43 m, while Ux is governed by loading Case 1 with a maximum displacement of 0.44 m. In the case of the Edge model, loading Case 2 gives the highest displacements in both x and y directions, equal to 0.43 m and 0.41 m, respectively.

Loading Case 2 controls in the Central model with displacements Ux equal to 0.44 m and Uy equal 0.45 m. More important than specific displacement values for each model, however, is the fact that all buildings now satisfy the serviceability criterion of a maximum roof displacement of 0.5 m established for the buildings. It is also important to note that the analyses serve to identify in a conceptual context the type of structural system required to provide an acceptable structural solution. A detailed design of each of the structural systems proposed lies beyond the scope of this paper.

TABLE II
LATERAL DISPLACEMENTS RESULT WITH SLLR FOR CASE 2 WIND LOADING

Configurations	stiffness eccentricities (m)		Maximum displacement service wind load P_{wx} and 0.75 P_{wx}		Maximum displacement (m) service wind load P_{wy} and 0.75 P_{wy}	
			With SLLR strength checked	With SLLR-serviceability checked	With SLLR strength checked	With SLLR serviceability checked
	X	Y	Ux (m)		Uy (m)	
Sides	13	3.9	0.87	0.45	0.88	0.46
Half Sides	10	5.4	0.98	0.44	1.16	0.43
Edge	9	12	1.24	0.43	1.36	0.41
Central	8	8	1.0	0.44	1.1	0.45

P_{wx} wind loading parallel to x-axis; P_{wy} wind loading parallel to y-axis.

VII. Supplementary Material Cost

The energy required to produce the structural elements has serious environmental and cost consequences. Different building types with different morphologies results in differing amounts of structural materials required, which in turn will impact economy and sustainability of the solutions. According to MEPS International (Ltd, Jul-2011), the cost of steel structural sections are $908/t (metric tonne), ($824/ton). Cost of structural concrete varies by region and country. However, for the Boston region, the costs have been estimated using national RS Means data (RS Means 2011), where it is $640 /m3 ($489.3 /yd3) for normal weight concrete including materials, framing, placing, labor, and also including 100 kg/m3 (168.6 Ib/yd3) of reinforcement. Also, the cost of one tonne of steel is $4300 including materials, fabrication, primer, and erection of bolted connections. Using the quantities of the materials needed for the structural elements for the BSS and SLLR systems, a comparison between the normalized costs for the four models can be made, as summarized in Table III.

The results in the table III are normalized using the cost of the Sides configuration as a basis. Table III illustrates that the highest cost spent in concrete is in the Edge configuration (63% higher than the cost in the Sides configuration); in addition this configuration demands a high cost of steel for the SLLR system, 44% higher than the cost in the Sides configuration. These simple calculations clearly show that there is a heavy penalty in building cost to achieve an adequate structural solution for the Edge configuration, one where the BSS as conceived for environmental performance was severely flawed. The highest cost of steel is found in the Half Sides configuration; in contrast, this configuration has the lowest cost of the concrete. Because the Half Sides configuration demands the highest amount of steel than any other configuration, the structural solution results in the most costly configuration. The total cost in the Central configuration is 22% higher than the cost in the Sides configuration. The Sides configuration resulted in the lowest overall cost in this study.

TABLE III
COMPARISON OF NORMALIZED COST

	Material quantity		Unit Cost		Normalized cost		
					Partial		Total
configuration	Steel (t) From SLLR	concrete (m^3) From BSS	SLLR Steel ($/t)	BSS Concrete ($/$m^3$)	SLLR Steel	BSS Concrete	
Central	10189	8633	4300	640	1.26	0.96	1.22
Edge	11653	9874			1.44	1.63	1.39
Half Sides	15142	5505			1.87	0.61	1.69
Sides	8095	8976			1.0	1.0	1.0

The cost is normalized with respect to material cost in the Sides configuration.

VIII. CONCLUSION

Four building morphologies for high-rise buildings proposed by Yeang (1999) to minimize the energy consumption of buildings were studied to assess the impact on structural performance of design choices made with energy performance in mind. We found that the base structural system (BSS) of these building types requires supplemental lateral load resistance (SLLR) to achieve satisfactory structural performance. Preliminary conceptual design of the SLLR system further revealed that serviceability limits on building drift under wind loading controlled the design of the lateral load resisting system. The results obtained show that using a structural concrete core in combination with an outrigger system effectively reduced the roof lateral displacements of 200 m tall buildings subjected to wind loading typical of the Boston region, and the SLLR was designed so that lateral drift was essentially equivalent in all buildings. Our analysis leads to the following key conclusions:

(1) In all cases an SLLR (we used a steel braced frame) was required to supplement the stiffness of the BSS.

(2) Two of the three configurations undergo substantial torsional deformations under wind loading, and therefore require substantial additional stiffening.

(3) The trade-off of placing the structural walls to maximize operating energy efficiency is too great. The potential irregularity in the rigidity, caused a substantial growth cost (about 40% more than normal cases) in materials that reflected negatively on the total cost.

These findings quantify the potential impact on structural performance of consideration of energy performance in the design of the primary lateral load resisting system of a high-rise building, and illustrate the complex interactions that occur between the structural and environmental performance of the structural system. Coupled with other recently published work, this paper forms the basis of a framework for the integrated analysis and design of high-rise structural systems for enhanced energy performance within the constraints imposed by structural requirements, and identifies as cost, operating, and embodied energy as the key non-structural considerations in executing such a design. Architects, mechanical and structural engineers, working together in integrated design teams may be able to apply such an analysis process to develop new structural morphologies that allow high-rise buildings to achieve new levels of life-cycle energy performance while continuing to meet structural requirements.

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