The Application of Aerodynamic Optimization to Mitigate Wind Loads on High Rise Buildings and Produce Green Energy

Victoria Q. Sun

Abstract— Wind resistance is an important factor that is considered in the design of a building, as it has potential to mitigate negative effects of wind such as deformation and resonance. In this research project, aerodynamic optimization of building modifications was applied to determine the best treatment that improves the wind resistance of a building while utilizing structure shape for wind energy generation. Building design modifications included in this study were: rectangular (control), middle split and top opening. Each building design modification was placed inside the virtual wind tunnel for simulation using a computational fluid dynamic software. Virtual simulation results such as wind flow, stress, and building deformation from the wind load were studied and compared. When comparing to the baseline, the stress on the building with top opening is reduced by 44.19%. Among all 3 different models, the building design with top opening also has the least deformation and could generate 3 times more power than the building with middle split.

Index Terms— aerodynamic optimization, green energy, high rise buildings, wind load mitigation

1 Introduction

Wind resistance is a crucial factor in the structural integrity of the building, and it is considered during the design and construction process of buildings. One approach to improve building wind resistance is to use "Aerodynamic Shape Optimization" techniques. This involves the definition of objective functions that specify the goals of the optimization, design variables that determine the aerodynamic shape, as well as constraints that define a feasible region of the design space [1].

A second strategy to increase wind resistance of buildings is to use "Aerodynamic Mitigation" techniques [1]. These methods effectively use simple and innovative architectural features to modify the aerodynamic shape of the buildings to reduce the wind loads. Many past researches focused in this area [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. Aerodynamic modification techniques aim particularly at suppression of vortex shedding and can generally be classified into two groups: 1) minor modifications, 2) major modifications [2], [13], [14].

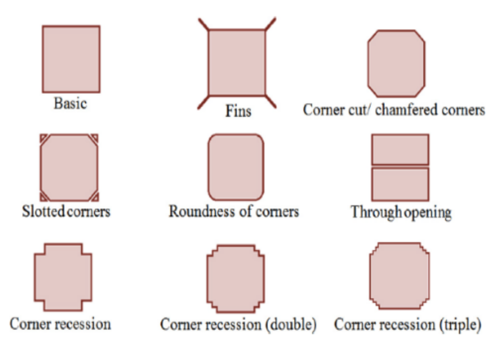

Fig. 1. Aerodynamic mitigation with minor modifications

While minor modifications as shown in Fig. 1 have negligible effects on the overall structural and architectural design of the building, major modifications have significant effects. As shown in Fig. 2, varying the shape of building and setbacks along the height, tapering, inclusion of openings at top and twisting the building are among the major modification methods that can be utilized to design aerodynamically favorable building shapes.

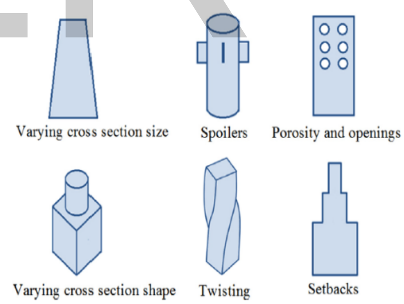

Fig. 2. Aerodynamic mitigation with major modifications

Addition of openings or porosity to a building will allow air to bleed through the building via openings or porous sections, and the formation of the vortices becomes weakened and disrupted by the flow of air through the structure. This aerodynamic modification method has been investigated by several researchers [6], [7], [8], [12]. These studies showed that openings in the upper half of the buildings can be very effective for reducing the across wind response of high-rise buildings.

This research will focus on effect of different opening designs in the building on its wind resistance and how these openings could be directed towards green energy production. To avoid traditional "cut and try" approach for the design of new aerodynamic shapes, computer simulation was used to compare and select the opening design that is the most beneficial to the wind resistance of a building and at the same time it can

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produce the most green energy.

2 Modeling and Simulation Set-up

2.1 Baseline Model

The United Nation Headquarter (UNHQ) building was chosen as baseline control model. The UNHQ building as shown in Fig. 3a stands on the eastern shore of Manhattan Island, on the banks of New York City's East River. It consists of 39 stories above ground and three stories underground. With steel concrete body, the UNHQ building is 115,824.00mm (380 feet) long, 48,768.00mm (160 feet) wide and 155,448.00mm (510 feet) tall [15]. To reduce model size, 145:1 ratio is applied when constructing the 3D model of the UNHQ building. As illustrated in Fig. 3b, the baseline 3D model size is: 771.14mm long, 322.09mm wide and 1036.32mm tall. 3D Stress sensor was modeled at bottom of the building. The sensors are distributed evenly by 3x5 array. Stress data will be collected at these locations for results analysis.

(a) (b)

Fig. 3. Baseline model used in this study. (a) photo of UNHQ building; (b) 3D model of UNHQ building after 145:1 scale down

2.2 Test Models

To prove the concept and verify the hypothesis, 2 modifications were simulated for the UNHQ building: middle split and porous top opening. Fig. 4 shows the front and side view of the middle split design. The size of the spilt in the middle is 24mm, which is 11.42 feet in actual size.

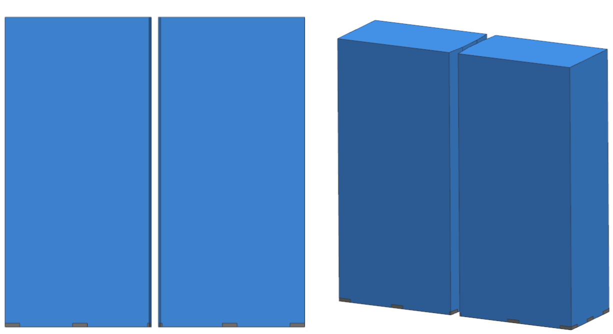

Fig. 4. Front and side view of the UNHQ building model with middle split.

Another modification to the building is to add top opening to the UNHQ building. As shown in Fig. 5, eight slots were added to top of the building. Each slot is 331mm wide and 36mm tall.

Same as baseline model, 15 stress sensors were added at the bottom of both models.

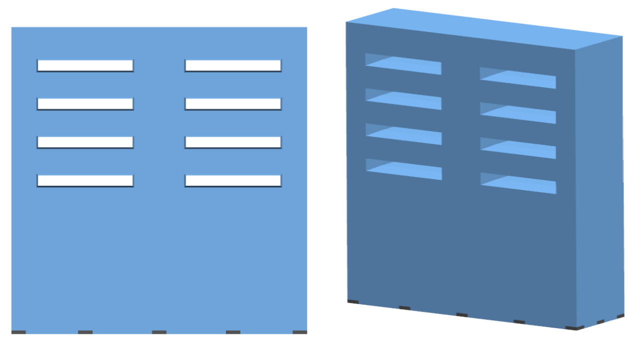

Fig. 5. Front and side view of the UNHQ building model with top opening

2.3 Wind Tunnel Assembly

The baseline and test models were placed at the same location in the wind tunnel model as show in Fig. 6. To reduce model size, only contraction, test and diffuser sections of the wind tunnel were modeled. Size of the test section is a 1700mm x1700mm square with length of 7000mm.

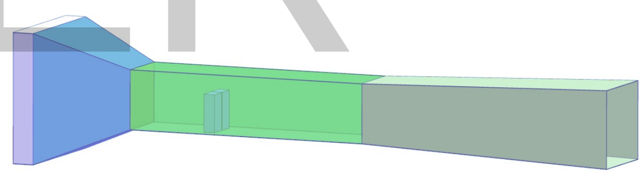

Fig. 6. Model of wind tunnel with testing piece.

2.3 Meshing

As shown in Fig. 7, the wind tunnel and test piece assembly were surface meshed first, and then volume meshed with tetrahedral elements. To keep meshes of different modeling iterations consistent, same element sizes were used for all models.

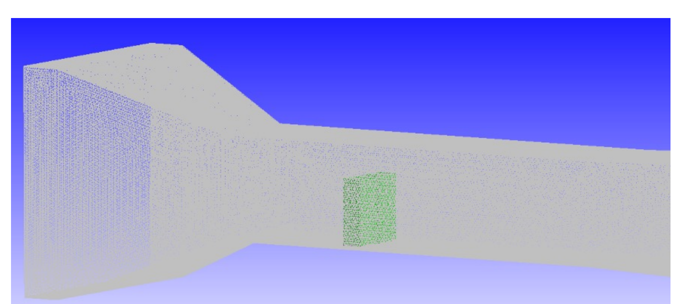

Fig. 7. Model of wind tunnel with testing piece.

Mesh of baseline model and 2 modifications were shown in

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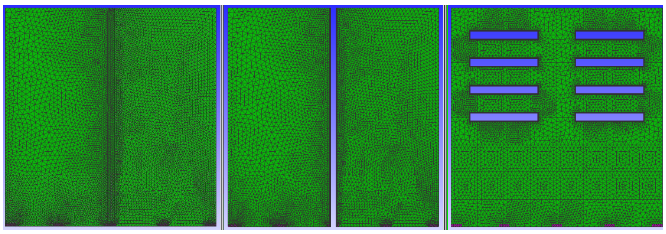
Fig. 8. To ensure enough elements and nodes are in the middle split and top opening slots, element size of 8mm was used for these areas, while element size of 20mm was used for rest of the building body.



(a) (b) (c)

Fig. 8. Meshed baseline and test pieces. (a) Baseline; (b) Middle split; (c) Top opening

2.4 Boundary Conditions and Material Properties

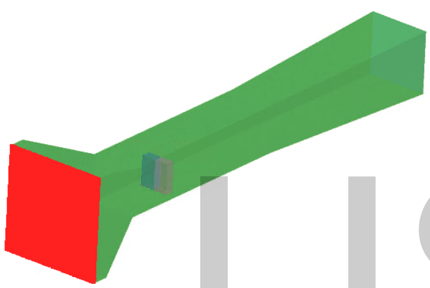


Fig. 9. Inlet for wind tunnel

Area of air inlet for wind tunnel is shown in Fig. 9. The inlet velocity used for all modeling iteration were kept the same at 10m/s. Fig. 10 shows displacement lock down for the wind tunnel and test pieces. These boundary conditions will ensure wind tunnel and base of the building will not shift or move during stress and deformation computation.

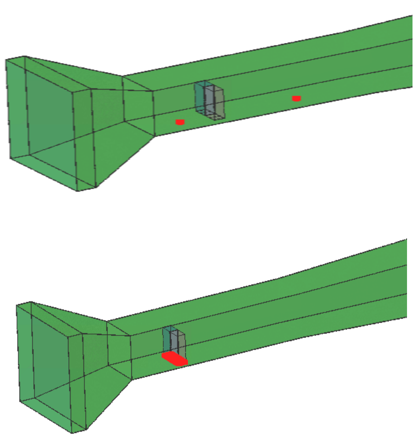


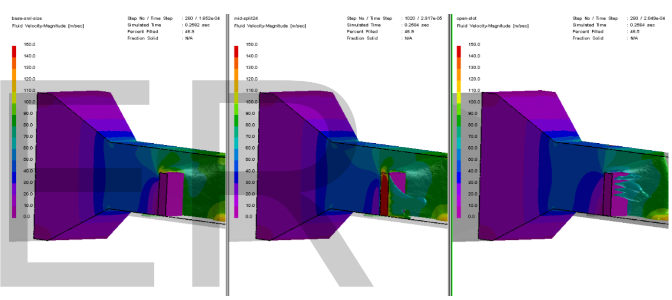
Fig. 10. Zero movement boundary to lock down wind tunnel and base of test pieces.

Materials involved in the modeling and simulation are air for fluid in the wind tunnel, plain steel for wind tunnel walls and steel concrete mixture for the control and test building models. Again, to keep consistency between models, properties of all these materials were kept the same for all the modeling iterations. The only difference between models is building design modifications.

3 Results and Analysis

3.1 Flow Field Around the Building

Flow field in the wind tunnel was analyzed and compared among baseline and the two modifications. Velocity distribution of all 3 iterations were shown through a section view in Fig. 11. The wind tunnel and the test pieces were sectioned through the middle. The color scaled shows velocity in m/s. When all buildings are directly facing the wind, backside the baseline building has no wind at all and form a low-pressure cavity, while middle split and top opening design allows wind pass through. The building with top opening has the most wind passing through. The wind speed in the middle split and top opening were used later for wind power generation.

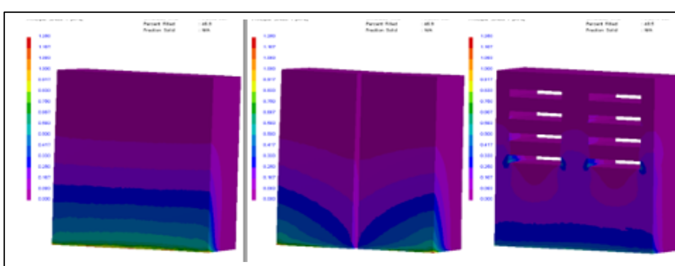


(a) (b) (c)

Fig. 11. Wind speed distribution at section view of the wind tunnel. (a) Baseline; (b) Middle split; (c) Top opening

3.2 Stress on The Building During Wind Load

To further study effect of aerodynamic modifications on wind resistance of the building, stress on the building from direct wind load was analyzed and compared among all 3 modeling iterations. Color maps in Fig.12 are visual comparison of stress distribution on the buildings. To make comparison logistic, stress values of all 3 maps are colored with same scale from 0 to 1.2MPa. It is obvious that the building design with top opening has the lowest stress.



(a) (b) (c)

Fig. 12. Distribution of stress on the building during wind load. (a) Baseline; (b) Middle split; (c) Top opening

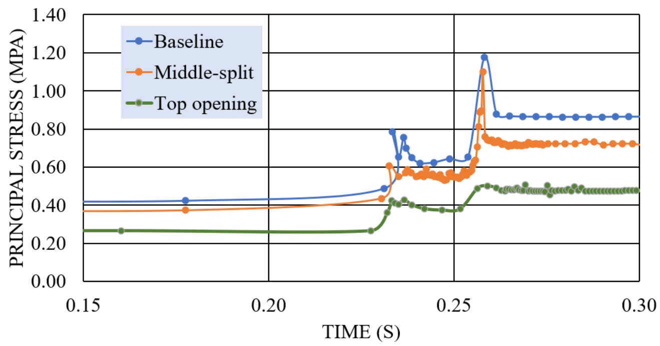


Fig. 13. Comparison of stress distribution on the building during wind load.

Stress-time profile from the middle stress sensors of all designs were extracted from the modeling results. Fig. 13 shows comparison of stress on the building during the whole course of the simulation tests for all three building designs. Shortly after the wind flow pass through the building, the stress level on the building reached a stable value. As indicated in Fig. 13, building design with top opening had the lowest stress level among all three designs. When comparing to the baseline design, the stress on the building with top opening is reduced by 44.19%.

3.3 Building Deformation During Wind Load

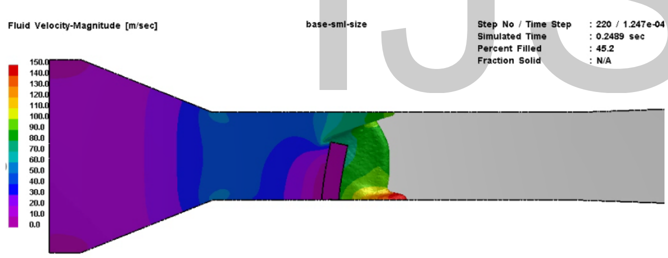
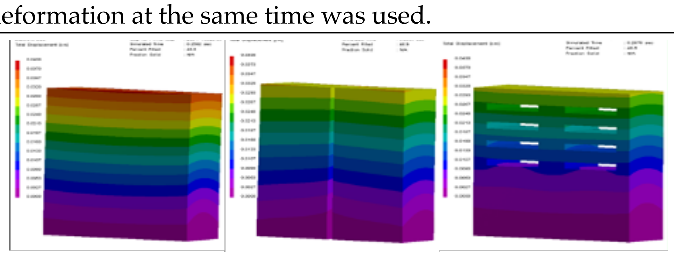


Fig. 14. Illustration of building deformation during wind tunnel test

To better visualize the building deformation under wind load, the size of the deformation was scaled up 100 times. Fig. 14 shows building deformation after 100 times of magnification. Under the force of the wind, the building was bent and curved. Comparisons of the building deformations with different design are shown in Fig. 15. To make fair comparison, the building deformation at the same time was used.


(a) (b) (c)
Fig. 15. Distribution of stress on the building during wind load. (a) Baseline; (b) Middle split; (c) Top opening

As shown in Fig. 15, comparing to baseline design, both designs with middle split and top opening have less deformation. Among all three designs, the building with top opening has the least deformation. The aerodynamic modification to the building not only reduces the stress, but also lowered the building deformation during wind load.

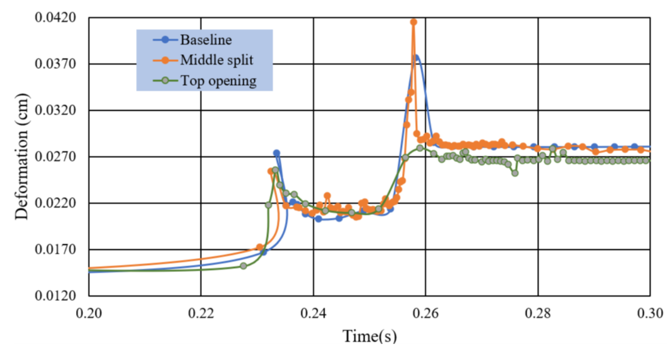


Fig. 16. Comparison of building deformation during wind load.

Building deformation size during the whole simulation is shown in Fig.16. Same as stress profile shown in Fig. 12, the building deformation of all three models stabilized around a constant value. Comparing all three different designs shown in Fig. 16, the building with top opening has the least deformation.

3.4 Green Energy Generation

As indicated by above study, wind resistance of the building is improved through aerodynamic modifications, especially the design with top opening. Conceptually, if all the opening area is used to generate green power with wind turbines, it could add economic justification to leave the empty space at design stage. In the following, green power generation will be examined to see how much power it can provide assuming there is no other tall building around and the building will face the wind directly.

According to Irwin, Kilpatrick and Frisque [16], wind power generated per square meter per year can be calculated using the following equation:

$$P = \frac{1}{2}\rho V^3 T \qquad (1)$$

P – Power generated per square meter per year, KWh/(yr.m2)
ρ – Density of air, 1.2kg/m3
V - Wind speed at the turbines, m/s
T – Number of hours in a year, ~8766hrs

Assuming average wind speed facing the building is 15MPH (6.71m/s), wind power generated per square meter per year is P = 1517KWh/(yr.m2). Using the open area of the building, the wind power generated by the baseline building and two modifications is shown in Table 1. To be conservative, 40% overall energy conversion efficiency was used during the calculation.

As shown in Table 1, the design with top opening could generate about 3 times more power than middle split design.

TABLE 1
WIND POWER GENERATED THROUGH OPENING OF BUILDING

	Baseline	Middle Split	Top opening
Opening Area (m^2)	0	580.29	2144.88
Total power generated (MWh/yr)	0	352.12	1301.51

CONCLUSIONS

Using computer simulations, the 145:1 scaled down UNHQ building and two of its aerodynamic modifications were studied in the wind tunnel to increase its wind resistance and generate green energy. Building stress and deformation during the wind load, as well as potential green energy it could generated were compared. It is shown that:

1. When comparing to the baseline design, the stress on the building with top opening is reduced by 44.19%.
2. With similar trend, the building design with top opening has the least deformation during the wind tunnel simulation test.
3. The building with the top opening could generate about 3 times more power than the building with middle split.

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