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Study of wind tunnel test results of high-rise buildings compared to different design codes

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Abstract.   Several international codes have been developed for evaluating wind loads on structures; however, the wind structure interaction could not be accurately captured by these codes due to the gusty nature of wind and the dynamic behavior of structures. Therefore, the alternative wind tunnel testing was introduced. In this study, an introduction to the available approaches for wind load calculations for tall buildings was presented. Then, a comparative study between different codes: the Egyptian code, ECP 201-08, ASCE 7-05, BS 6399-2, and wind tunnel test results was conducted. An investigation has been carried out on two case studies tall buildings located within the Arabian Gulf region. Numerical models using (ETABS) software were produced to obtain the relation between codes analytical values and wind tunnel experimental test results for wind loads in the along and across wind directions. Results for the main structural responses including stories forces, shears, overturning moments, lateral displacements, and drifts were presented graphically in order to give clear comparison between the studied methods. The conclusions and recommendations for future works obtained from this research are finally presented to help improving Egyptian code provisions and show limitations for different cases.

Keywords: tall buildings; wind tunnel test; Egyptian code; ASCE 7-05; BS 6399-2; drift control

1. Introduction

In the past few decades, several international building codes and standards have been developed and established for evaluating the effect of wind loads on flexible tall buildings, taking into account the influence of structural geometry, surrounding constructions, terrain and site exposures, and wind characteristics as well (Aly *et al*. 2011). However, the actual wind structure interaction was not always accurately captured by these standards due to the gusty nature of wind flow and the complicated dynamic behavior of structures (Heiza and Tayel 2012). Building exposure with respect to surrounding structures could have major impact on the applied wind loads according to different structural shape, which is not exactly captured by codes. Therefore, irregular structural shapes and complex geometries are not recommended to be studied by the codes conventional procedures

As a result of the above, the need for alternative methods to evaluate wind loads on buildings

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and other structures became a must in order to give accurate wind pressures on super tall buildings and special structures which are not often covered by these standards. Thus, three alternatives were introduced; the first alternative is the full scale measurements of structures (FSM), which is used to evaluate wind loads only on existing structures. The second alternative is the computational fluid dynamics (CFD), which is still under research and not yet released, as in some situations it yields fake results. The third alternative used in this study is the wind tunnel testing (WTT) of structures, which is the most accurate method used to evaluate wind loads on all types of buildings and structures

McNamara (2001) checked the Massachusetts State Building Code and National Building Code BOCA 93. It was concluded that wind tunnel predicts more pressure at 100 m and above, but diminished quickly on lower floors.

But, Zhou *et al.* (2002) presented a comprehensive assessment of the source of results scatter in the along wind loads recommended by major international codes including the ASCE 7-98, AS 1170.2-89, NBC 1995, AIJ 1993, and Eurocode 1993. It was noted that this scatter arises primarily from variations in the definition of wind field characteristics in the respective codes and standards, including the mean wind velocity profile, turbulence intensity profile, wind spectrum, turbulence length scale, and the wind correlation structure.

In 2003, Kikitsu *et al.* (2003) made comparative study on the peak pressure coefficients among several international codes and standards, including the ISO 4354-1997, Eurocode 1995, ASCE 7-98, AS/NZS 2002, NBCC 1990, SS 1989, and finally the BSLJ 2000. It was pointed out that the degree of discrepancy in peak pressure coefficients is 0.25 – 0.40 for windward wall, 0.20 – 0.30 for leeward and side walls, and 0.20 for flat roof.

Belloli *et al.* (2009) compared the wind loads measured experimentally in wind tunnel tests and those predicted by Eurocode on a high slender tower. It was found that Eurocode may underestimate the effect of certain exposures.

Also, Bhami *et al.* (2009) compared the Indian standard (IS 875) and code (NBC 2005) for wind induced loads to the wind tunnel test data. The results indicate that IS 875 pressure values on edges stand much lower than wind tunnel test and ASCE figures. Au and To (2012) validated the dynamic wind load predicted by a wind tunnel model with the values identified from full-scale field vibration data of a super-tall building in Hong Kong. Reasonable agreement is observed between the wind tunnel model predictions and the values identified from field data.

Furthermore, Holmes (2014) found significant differences in the predictions of along-wind base moments for a generic tall building from several wind tunnels compared to the Hong Kong Code of Practice of 2004, the Australian/New Zealand Standard, and the American Standard (ASCE 7). Only the Australian/New Zealand Standard gave predictions close to the averages of the wind-tunnel data for the cross-wind moments.

Sepe and Vasta (2014) aimed to obtain a reduced model for the wind field used in experimental aerodynamic tests of high-rise buildings. Experimental data showed that the first few blowing modes can effectively represent the wind-field when eigenvectors of the power spectral density tensor are used, while higher modes can play a non-negligible role when the covariance wind tensor is used to decompose the wind field.

Liang *et al.* (2014) investigated the three dimensional equivalent static wind loads of symmetric high-rise buildings, based on the wind tunnel data and using the mode acceleration method. They found that equivalent static wind loads in along-wind and across-wind directions were at the same order of magnitude. Therefore, the combination effects of three dimensional wind loads on super high-rise buildings should be considered in the same time for their structural wind-resistant design.

In this research, a comparative study was conducted between the ASCE 7-05, BS 6399-2, and ECP-201-08 codes analytical procedures, as well as the wind tunnel experimental tests, for evaluating the wind induced lateral loads in the along and across wind directions. The conclusions obtained and the recommendations for future work were all presented in later section.

2. Main objectives

In this research, two case studies located within the Arabian Gulf region, and having a height range of 200 to 300 m, were selected to establish a comparative study between the codes analytical methods and the wind tunnels experimental test results. Their plans are rectangle and near triangle. The main scope and objectives of this study can be summarized in the following points:
1. To present an introduction to the wind engineering problem, including explanations of the wind climate and characteristics.
2. To review the historical works and literature studies made on comparing wind tunnel tests results to the corresponding international codes values.
3. To produce numerical models using (ETABS) software, in order to obtain the along and across wind structural responses for each case study.
4. To illustrate graphically a comparative study between the ASCE 7-05, the BS 6399-2, the ECP 201-08, and the wind tunnel tests outputs.

3. Wind engineering approaches

Several international buildings codes of practice give their own limitations and recommendations for calculating wind loads of structures, which correspond to the local wind climate and exposure category of each region (Ming 2010). Out of these international codes, two majors were selected to discuss in detail their provisions for wind loads on buildings, along with the Egyptian Code, in order to be compared to the wind tunnel results:
1. American Society for Civil Engineers: Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-05: Chapter 6: Wind Loads 2006).
2. British Standard: Loading for Buildings (BSI 6399-2: 1997 corrected 2002: Part 2: Code of Practice for Wind Loads 1997).
3. The Egyptian Code for Calculating Loads and Forces in Buildings and Structural Works (ECP-201-08: Chapter 7: Wind Loads 2008).
4. Wind Tunnel Testing (WTT) Method.

3.1 ASCE/SEI 7-05

In ASCE 7-05 gives three procedures for calculating wind loads on buildings:
1. Method 1: Simplified Procedure.
2. Method 2: Analytical Procedure.
3. Method 3: Wind Tunnel Procedure.
Method 1, the simplified procedure, is restricted to regular shaped buildings with a maximum height of 18 m. This method gives the wind pressures on buildings directly without calculations when the building meets the above conditions.

Method 2, the analytical procedure, can be used for high rise buildings that are regular in shape, but they should not be sensitive to cross wind loading, vortex shedding, instability due to galloping or flutter; and does not have a site location for which channeling effects or buffeting warrant special consideration. This method applies to a majority of buildings, as it is taking into account most of the main factors related to the wind engineering problem.

Method 3, the wind tunnel procedure, which is recommended for buildings with irregular and complex shapes, flexible with natural frequencies less than 1 Hz, subject to cross wind loading and vortex shedding or where a more accurate wind pressure distribution is desired.

In this study, the analytical procedure is applied and the design wind loads for buildings at height Z above ground level was determined according to the following equation (1) (ASCE 7-05 2006).

$$P = q_z \, G_f \, C_p \text{ (windward)} + q_h \, G_f \, C_{pi} \text{ (leeward)} \tag{1}$$

Where, G_f is the gust effect factor that accounts for the dynamic amplification of loading in the along wind direction due to wind turbulence and structure interaction. There are three methods for calculating the gust effect factor (G_f) in (ASCE/SEI 7-05 2006) depending on structure rigidity. The external pressure coefficients (C_p) and the internal pressure coefficients (C_{pi}) shall be determined from Tables in (ASCE 7-05 2006).

The velocity wind pressure q_z at height Z and the velocity suction q_h are given by equations in (ASCE/SEI 7-05 2006). (G_f) does not include allowances for the across wind loading effects, vortex shedding, and instability due to galloping, flutter, or dynamic torsion effects. Buildings susceptible to these effects should be designed using the wind tunnel test results.

3.2 BS 6399-2: 1997

Two methods are introduced by the BS 6399-2: 1997 for calculating wind loads on buildings and structures, in addition to its recommendations for wind tunnel testing:

     1. Standard Method.
     2. Directional Method.

The standard method is simpler than directional method, but it does not account for gust peak factor or wind directions, and is limited to 100 m maximum building height, whereas the directional method is valid up to 300 m height and accounts for all factors. A hybrid combination of both methods is advised by the BS code.

The procedure for calculating wind loads on buildings using the standard method can be summarized as follows (BSI 1997)

$$p_e = q_s \, C_{pe} \, C_a \tag{2}$$
$$p_i = q_s \, C_{pi} \, C_a \tag{3}$$

$$p = p_e - p_i \tag{4}$$

Where (q_s) in N/m^2 is the dynamic pressure. (p_e). (p_i), and (p) are respectively external, internal and net pressures. (C_{pe}), (C_{pi}), and (C_a) are the external and internal pressure coefficients and size effect factor respectively. All factors can be calculated from equations in (BSI 1997).

$$P = 0.85 \times \left(\sum P_{front} - \sum P_{rear} \right) \times (1 + C_r) \tag{5}$$

The overall load (P), where (P = pA) and (A) is the loaded area is calculated from (BSI 1997). Dynamic augmentation factor (C_r) is determined from Fig. 3.9 in (BSI 1997). The factor 0.85 in equation accounts for the non simultaneous action between faces. It should be noted that as the effect of internal pressure on the front and rear faces is equal and opposite when they are of equal size, internal pressure can be ignored in the calculation of overall horizontal loads on enclosed buildings.

The directional wind load method requires knowledge of the wind direction, the degrees relative to normal to each building face, represented by (θ), used to determine the pressure coefficients. The equation for calculating the overall load becomes

$$P = 0.85 \times [\textstyle\sum(P_{front}\,cos\theta) - \sum(P_{rear}\,cos\theta)] \times (1 + C_r) \tag{6}$$

The overall load on a building of arbitrary shape may be represented by the cases shown in Fig. 1 where the loaded area is taken as the smallest enclosed rectangle (BSI 1997).

3.3 ECP-2008

The method introduced by ECP-201-08 2008 for calculating the wind total force for high rise buildings is determined directly from

$$F = C_f\,k\,q\,A \tag{7}$$

Where: (A) is the area subjected to wind. (C_f) is the summation of external coefficients on the windward and leeward faces, the wind exposure height factor (k) is determined from tables in (ECP-201-08 2008), and (q) the wind direct pressure is determined from Eq. (8).
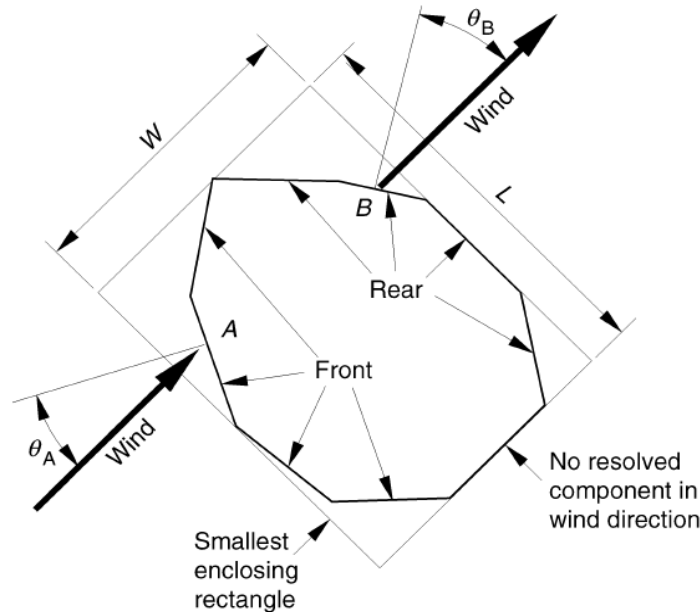

Fig. 1 General Case for arbitrary shaped building

$$q = 0.5\,\rho\,V^2\,C_t\,C_s \qquad\qquad (8)$$

Whereas V is the wind 3 second gust speed at 10 m above the ground for a return period of 50 years from the available wind climate data is determined, taking the air density in Eq. (8) as 1.25 kg/m^3,   the terrain topographic factor (C_t) is determined from (ECP-201-08 2008). The structural factor (C_s) accounts for the dynamic effect of both wind and structure, it is corresponding to the gust factor of ASCE 7-05.

3.4 Wind tunnel testing (WTT) method

The wind tunnel testing (WTT), which is the most reliable technique to expect wind loads on all types of structures. It is valid for complex shapes, irregular structures, and all buildings heights. Finally it takes into account effect of terrains and surroundings as illustrated in Fig. 2 by Davenport (2007). In wind tunnel tests, structures and surrounding buildings and features are converted from full scale into model scale based on consistent length, time, and velocity scales, in order to produce the correct full scale aerodynamic pressure coefficients. Fig. 2 is schematic of boundary layer wind tunnels (BLWT) model. Boundary layer wind tunnels (BLWT) typically have test section of width ranges from 2 to 4 m, height 2 to 3 m, and length 15 to 30 m, while the wind speeds are generally in the range of 10 to 45 m/s. The relatively long test section permits extended models of the upwind terrain to be placed in front of the building under test, as well as sufficient distance to develop appropriate boundary layer characteristics. The modeling is done in more detail close to the building and site, including:

• Different types of models are used for the various types of tests.
• Surrounding area and structures, typically constructed using blocks of wood and foam and extend for a radius of approximately 500 to 600 m.
• Coarsely modeled upstream terrains, chosen to represent the general roughness upwind of the site for particular wind directions.

  The model is mounted on a turntable to allow measurement of pressures for any wind direction, typically conducted for 36 wind directions at 10° intervals. Wind tunnel tests typically offer the following important benefits (Simiu 2009):

1. Provides accurate distribution of wind loads on structures, by determining the impact of the surroundings.
2. Provides predictions of wind induced building motions, accelerations, and torsion velocities.
3. Pretest estimate of cladding pressures to develop design of structure lateral loads resisting system.
4. Provides an assessment of expected pedestrian wind comfort criteria.
5. The overall design wind load is generally, but not always, lowers than code values, taking into account wind directions and surroundings effects.

Three basic types of wind tunnel modeling techniques are commonly used:
1. High Frequency Pressure Integration (HFPI).
2. High Frequency Base/Force Balance (HFBB/HFFB).
3. Aeroelastic Model (AM)

Pressure model provides local pressures for design of cladding and mean pressures for the overall design loads. Force balance model measures the overall fluctuating dynamic responses. Aeroelastic model is used for measurements of deflections and accelerations.

In this research, the pressure model test is used. Although it is primary used for obtaining cladding design pressures, the data acquired from the wind tunnel tests may be integrated to provide floor by floor shear forces for design of the overall (MWFRS), provided there is sufficient distribution of pressure taps. The advantage of this technique is that a single model used in a single testing session can produce both overall structural loads and cladding loads. However, the disadvantages are that the cladding pressure test model takes longer time to construct than a force balance test model. Also, like the force balance technique, it does not include any effect of the building motion through the air, such as aerodynamic damping; however, neglecting these effects is usually slightly conservative.

4. ETABS program analysis techniques

Computers and Structures, Inc (2011) and (ETABManE.htm) offered the widest assortment of analysis and design tools, including; multi-storey buildings, buildings with steel, concrete, composite or joist floor framing, flat and waffle concrete slab buildings, automated wind and seismic loads, multiple response spectrum cases, P-delta analysis, construction sequence loading analysis, multiple linear and nonlinear time history load cases, and much more.

Linear static analysis is used to obtain the structural induced responses of the study cases tall buildings under the effect of wind loads, taking into consideration the P-delta effects. However, modal analysis, using Ritz vector technique, is selected to estimate the structural dynamic properties such as mass distribution and participation ratio, overall stiffness, natural frequencies and periods, damping, and mode shapes. It should be noted that this study is concerned with the effect of wind loads in the along and across wind directions, in order to compare the codes analytical values with the wind tunnel experimental results.

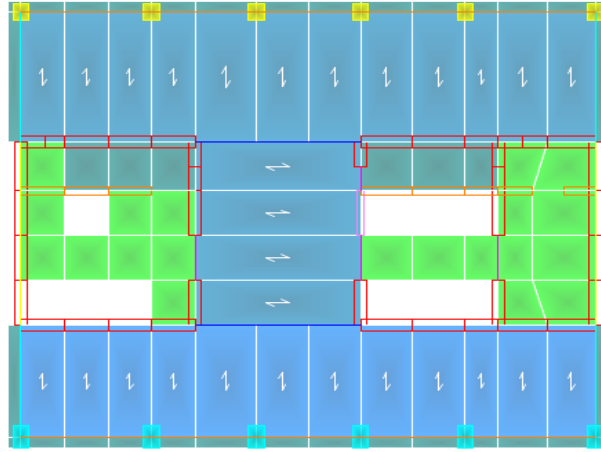Fig. 2 Schematic and internal view of wind tunnel test

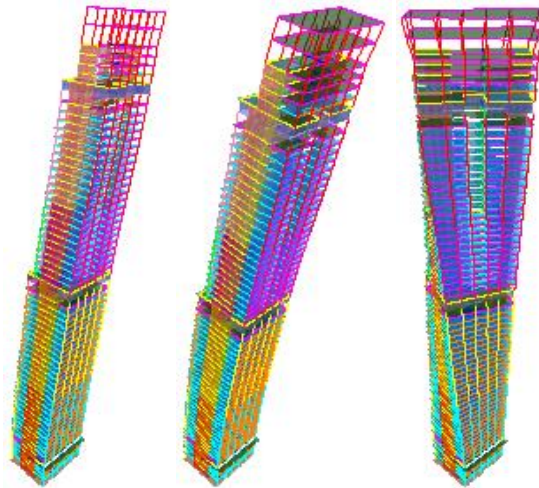Fig. 3 Typical floor plans for levels (4-16) for Rolex Tower

Fig. 4 Rolex Tower (ETABS) modal analysis

Generally, all wind tunnels testing produce the results in the three major directions; set of forces in (x) direction, set of forces in (y) direction, and set of torsion moments about (z) direction, where (x), (y), and (z) are the building three major dimensions. A set of recommended load combinations, typically 24, are provided by the (BLWT) consultant with the simultaneous application of the floor by floor wind loads. These load combinations represent the worst wind loading scenarios and are produced through consideration of structural responses to various wind directions, modal coupling, correlation of wind gusts, and the directionality of strong winds in the local wind climate

5. Case-study

Two case studies will be presented in this paper (Badry 2012): The Rolex tower in Dubai and the Lamar Tower in Jeddah. The Rolex tower is 250 meter height, rectangle shape plan (Figs. 3 and 4).

The next case study is Lamar tower in Jeddah with 295 meter height and its plan is near triangle (Figs. 5 and 6).
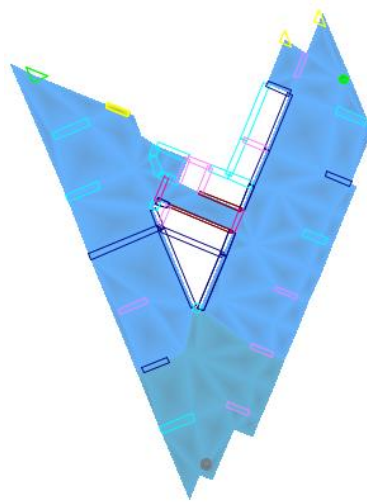
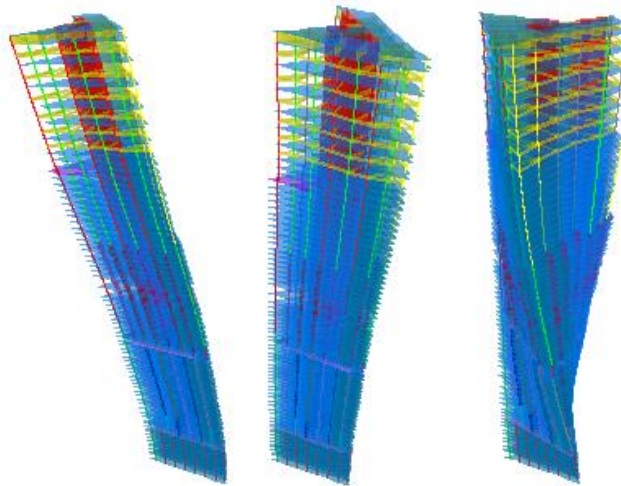Fig. 5 Floor plan at L15 for Lamar Tower-1

Fig. 6 Lamar Tower-1 (ETABS) modal analysis

6. Parameters of case studies

6.1 Fixed parameters

- Analysis Method: Linear static analysis is used.
- Main Wind Force Resisting System (MWFRS): Reinforced concrete dual system is used.
- Section Properties: Gross section properties for strength design and cracked section properties for serviceability checks are used (ACI 318R-05 2005).
- Diaphragm Type: Rigid diaphragm is used.

6.2 Variable parameters

- All buildings are Located within Arabian Gulf region. They are either residential, hotel, or office building.
- Number of stories is in range of 50 – 85 stories. Building heights are in the range of 220 – 300 m.
- Plans are rectangle, near rectangle, or near triangle. Height to width aspect ratio is in range of 1:4 – 1:8.
- Natural frequencies are in the range of 0.125 – 0.200 Hz and corresponding periods are from 5 – 8 seconds.
- Basic wind speed to ASCE and ECP codes is in range of 35 – 45 m/s, and to BS is in range of 20 – 30 m/s.

7. Results and discussions

A parametric study using graphical representation is performed on each of the case study buildings, in order to illustrate the relation between codes analytical values and wind tunnel experimental test results, for wind loads in the along wind and across wind directions expressed in terms of the followings (Taranath 2009): Stories forces, stories shears, overturning moments, lateral displacements, and inter story drifts between floors (ASCE Task Committee 1988).

Stories forces are the direct impact of wind load on each level, which depend on the elevation, height, and width of that level, as well as the applied wind pressure. It requires relatively stiff diaphragm to distribute the story force between the available vertical elements of the (MWFRS). Stories shears are the accumulative effect of stories forces over the height of building; or the summation of stories forces for all stories above the studied level. Overturning moments result from multiplying stories forces by the corresponding elevations above ground level, it should be noted that both the stories shears and moments are minimum at the building top level and maximum at the base. Lateral displacements are the horizontal movements of floors due to lateral wind loads, whereas the inter story drifts are the relative lateral displacements between two successive floors divided by the story height (Smith and Coull 1991).

Figs. 7-11 illustrates structural responses in the along wind directions of the first case study building; Rolex Tower. The Rolex case study shows almost similar results for all values except for the ECP 201-08, which always gave conservative values when compared to ASCE 7-05, BS 6399-2, or wind tunnel. Codes values for stories shears are almost linear, whereas the wind tunnel results are somehow curved. The wind tunnel test gave lower results in stories forces and shears in

the first 100 m height then the values of stories force are bigger than those of ASCE and BS. The wind tunnel results are closer to the ASCE 7-05 more than BS 6399-2 (Badri   2012).

Figs. 13-17 illustrates structural responses in the along wind direction of the second case study building; Lamar Tower-1.The results of the Lamar tower which has a near triangle plan not regular like the first case, are similar to that in the first case study, but with higher percentages of mismatching in results (Merrick and Bitsuamlak 2009). The ASCE 7-05 and BS results are closer to the ECP 201-08, while the wind tunnel test results are much lower than the codes in the first 150 m height then the values increase in the upper part to be close to the ECP 201-08 at the top (see Badri 2012). The results agreed with Kim *et al.* (2011). They have conducted response analyses for tall buildings with square plans with height variations using high-frequency force balance data, focusing on comparing the total accelerations of the various building shapes based on the shapes themselves, and not on different natural frequencies. For the tapered models, although the across-wind acceleration is larger than that of the square model, the along-wind and torsional accelerations are smaller than those of the square model, resulting in smaller total acceleration response.

The results for the across wind directions are negligible in the codes compared to the wind tunnel results (Holmes 2014) for the rectangular shape case and for the near triangular case (Figs. 12 and 18) This is very important issue because the forces are nearly neglected in the across directions in the studied codes(Badri 2012) .

Due to the complexity of acrosswind and torsional responses, physical modeling remains the only way to calculate them. Thus, all the standards recommend that extremely tall and irregular shaped structures be designed using wind tunnels. Few major codes developed empirical equations to estimate the acrosswind and torsional dynamic responses in preliminary design like the Japanese, Australian and Canadian codes. "ASCE 7 provides a comprehensive treatment of the along-wind response of flexible structures based on the Gust Factor Approach; however, ASCE 7, similar to many codes and standards, provides no guidance on the across-wind response" (Gerges and Benuska 2013).

Holmes (2014) compared cross-wind response and resultant acceleration predictions for three codes: the Hong Kong Code of Practice (2004), the Australian/New Zealand Standard , and the American Standard (ASCE 7). Only, the Australian code results were acceptable.

Therefore, in this study, the across wind responses are almost negligible for ASCE 5, BS and ECP codes.

ASCE 7 and Eurocode recently utilize partial loading to account for acrosswind and torsional loads. The partial loading technique simply applies fractions of the alongwind pressures in different combinations (Bashor and Kareem 2009).

8. Conclusions

The following conclusions are based on the results obtained in this study:

- Figures and charts investigated in the parametric study of this research can be used to facilitate the preliminary prediction of along and across wind loads on flexible tall buildings
- In general, the values of the overall effect of the across wind loading on tall buildings in the ASCE 7-05, BS 6399-2, and ECP 201-08 codes are almost neglected, as discussed

previously, by assuming it to have two equal side suctions on buildings envelopes. However, wind tunnel tests account for this effect correctly, and produce high values of across wind load.

- Buildings shape in plan and elevation has major influence on the degree of results agreement between the codes and wind tunnel tests outputs. Rectangular buildings produce the most similar results between codes and tests, whereas other buildings shapes produce conservative codes values for along wind direction when compared to tests results, depending on the degree of building shape irregularity in plan or elevation.

- The overall design wind loads obtained from wind tunnels are generally lower than that estimated by codes analytical procedures, which could have positive impact on the cost saving for tall buildings. At the same time, wind tunnel tests take into account the effects of surroundings, wind directions, and masses distribution, which are not accurately captured by corresponding codes and standards, making it the most accurate method for evaluating wind loads on all types of buildings and structures.

- The ECP 201-08 gives conservative wind loads and structural responses when compared to the ASCE 7-05, BS 6399-2, and to the wind tunnel test results for flexible tall buildings. On the other side, the ASCE 7-05 code gives results closer to wind tunnels outputs more than the BS 6399-2 or ECP 201-08 codes.

- All the ASCE 7-05, BS 6399-2, and ECP 201-08 codes show almost linear distribution of shear forces with the height above ground, whereas the wind tunnel tests results are somehow curved, this allows for a reduced overall effect of wind tunnel loads when compared to these codes values.
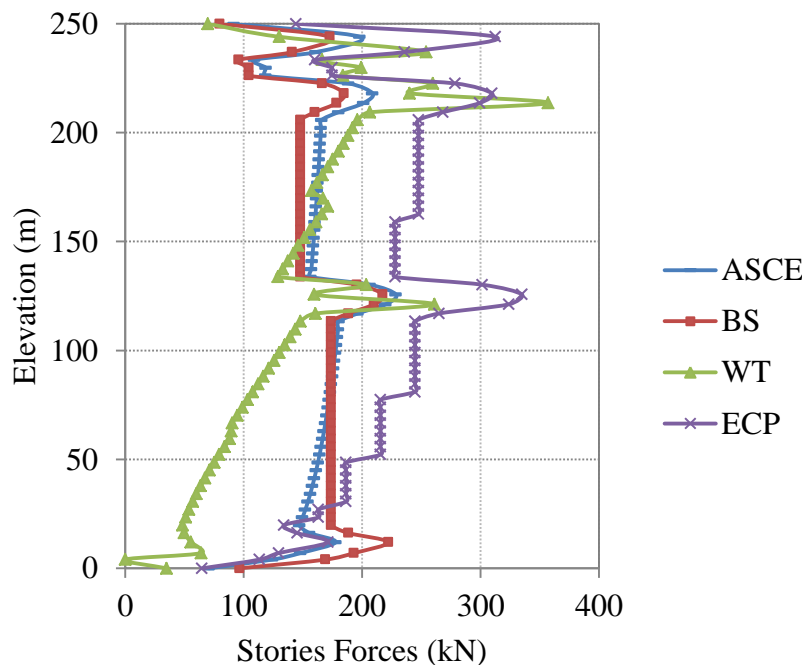

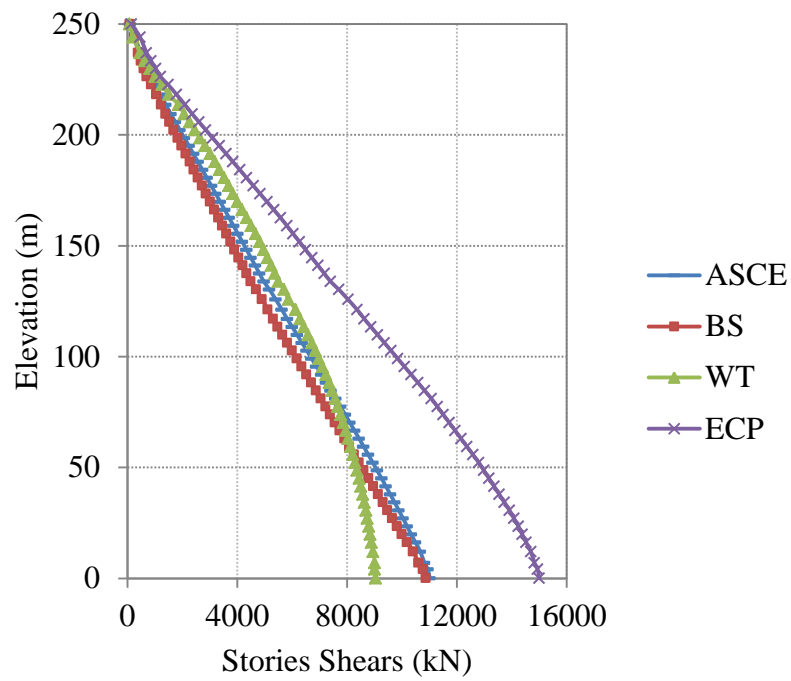Fig. 7 Along-wind stories forces in (x) direction for Rolex Tower

Fig. 8 Along-wind stories shears in (x) direction for Rolex Tower
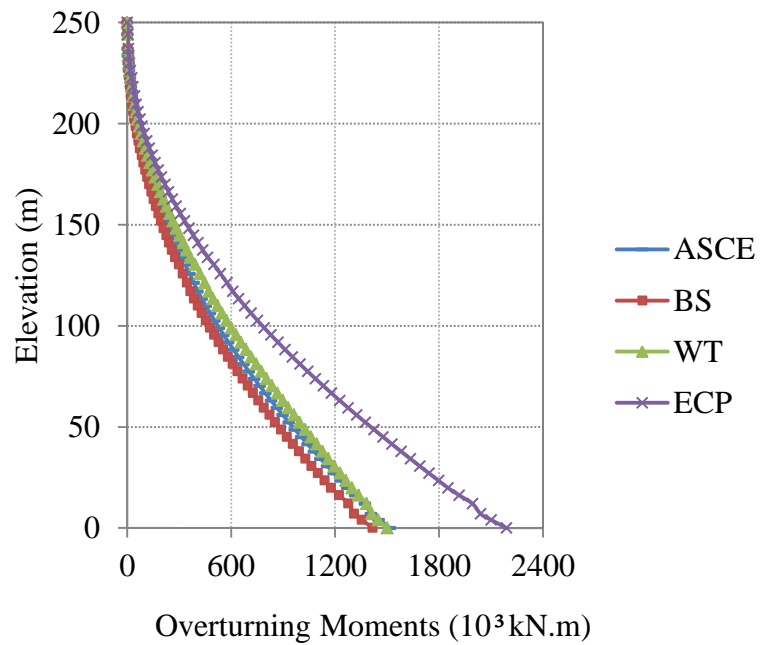

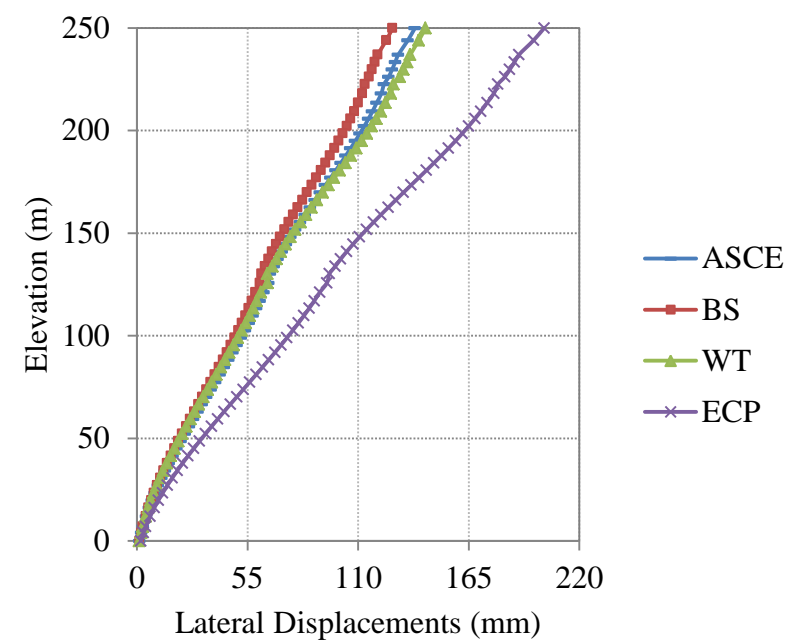Fig. 9 Along-wind overturning moments in (x) direction for Rolex Tower

Fig. 10 Along-wind lateral displacements in (x) direction for Rolex Tower
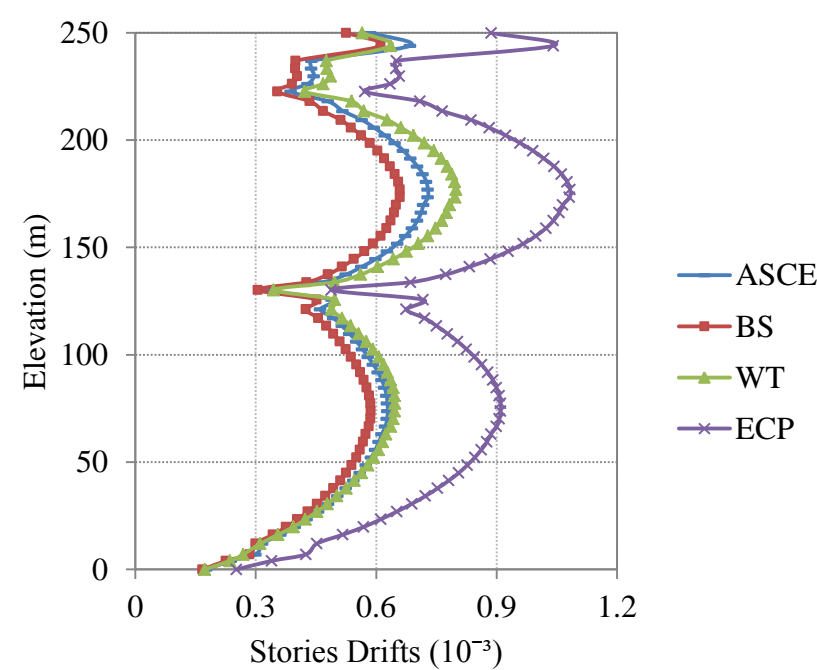

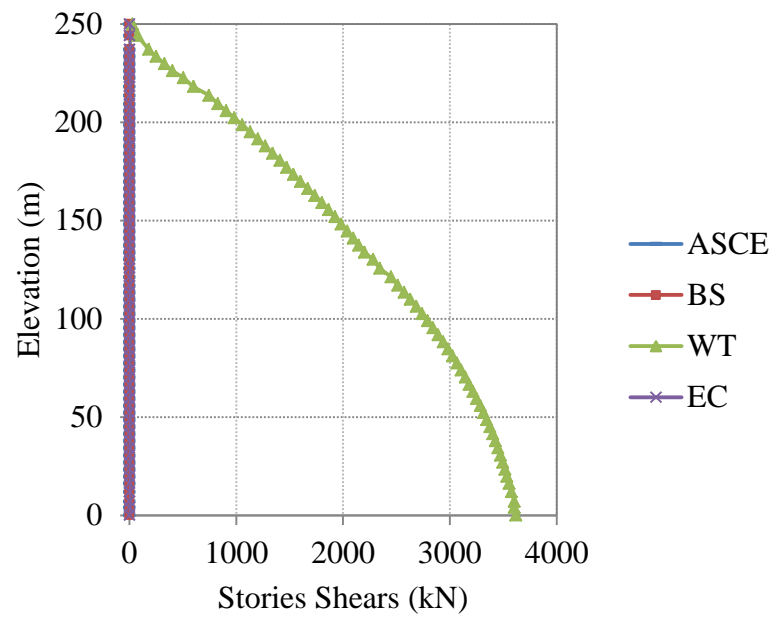Fig. 11 Along-wind stories drifts in (x) direction for Rolex Tower

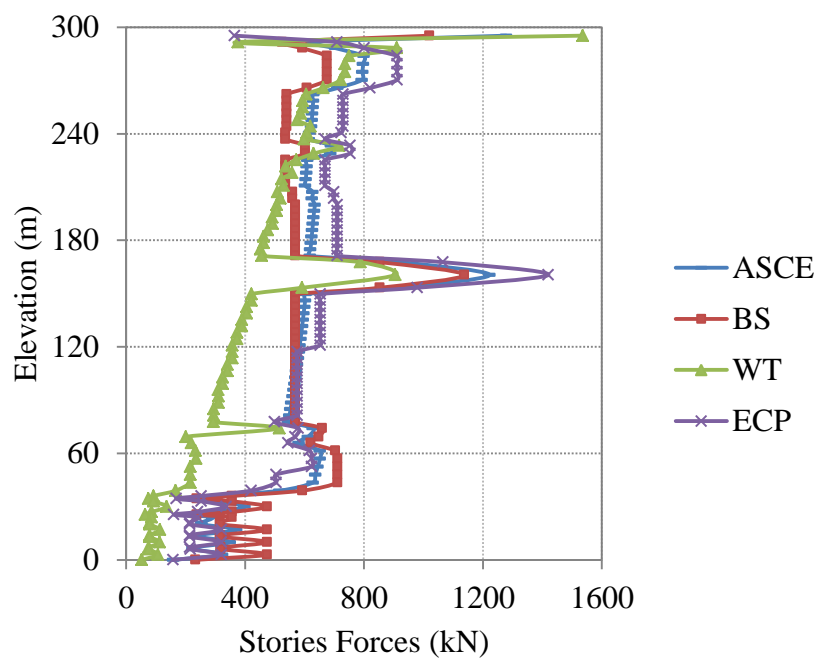Fig. 12 Across-wind stories shears in (x) direction for Rolex Tower

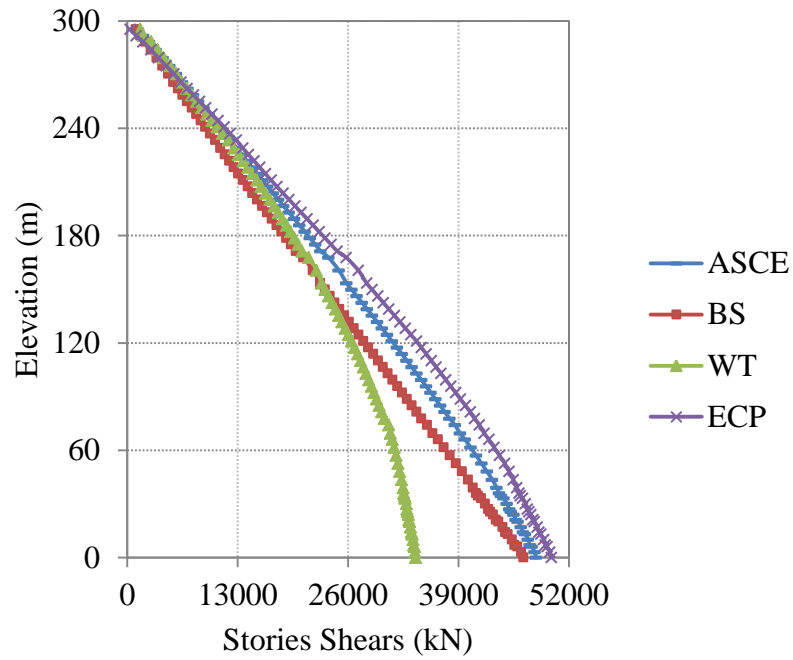Fig. 13 Along-wind stories forces in (x) direction for Lamar Tower-1

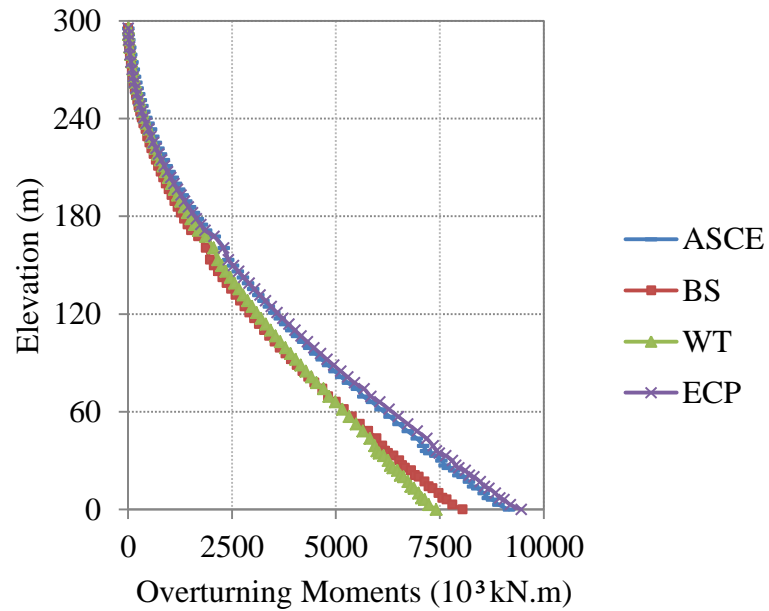Fig. 14 Along-wind stories shears in (x) direction for Lamar Tower-1

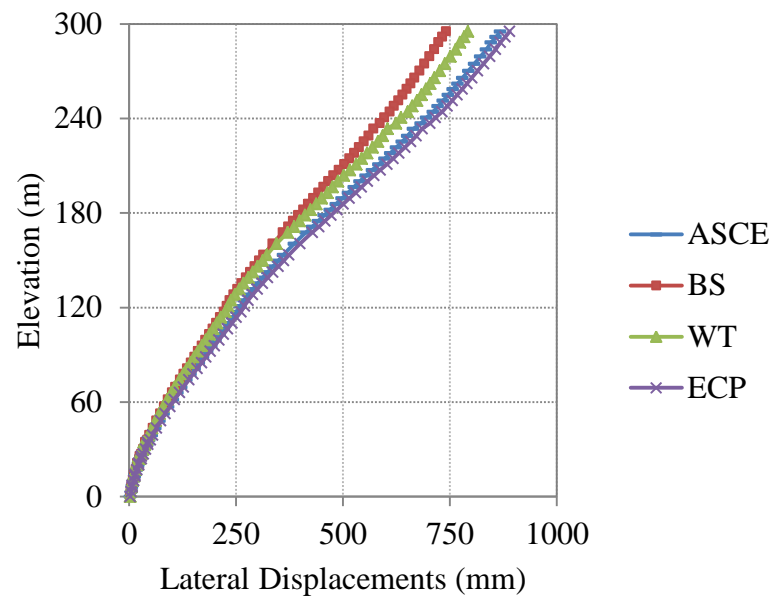Fig. 15 Along-wind overturning moments in (x) direction for Lamar Tower-1

Fig. 16 Along-wind lateral displacements in (x) direction for Lamar Tower-1
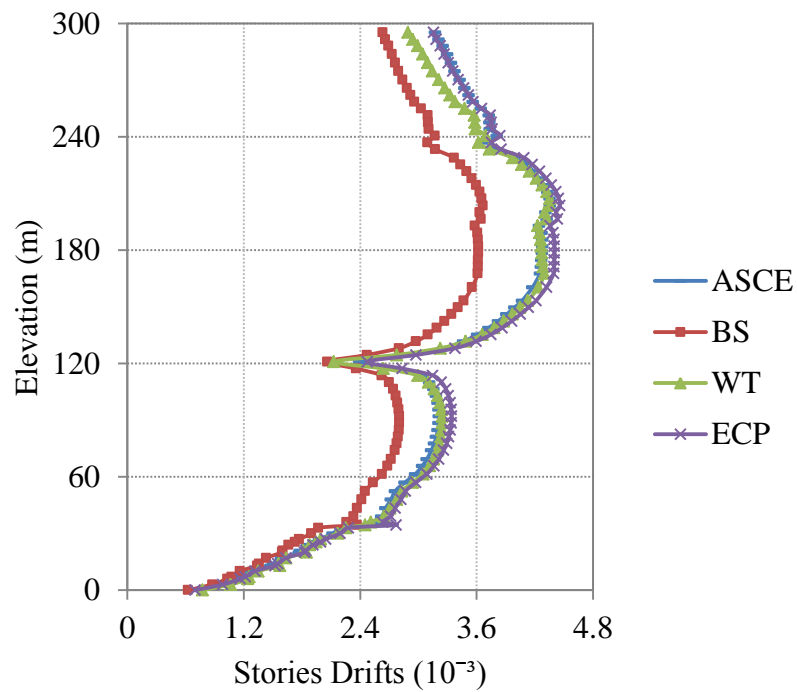

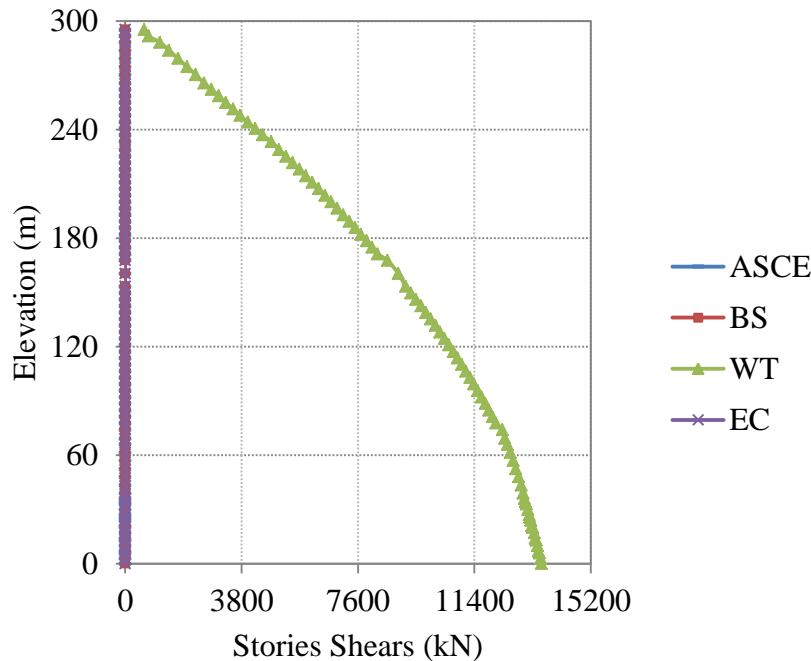Fig. 17 Along-wind stories drifts in (x) direction for Lamar Tower-1

Fig. 18 Across-wind stories shears in (x) direction for Lamar Tower-1

- Unlike the ASCE 7-05, ECP 201-08, and wind tunnel test; the BS 6399-2 does not reflect the wind velocity profile in its stories forces distribution; however, the corresponding story shears are similar to other codes and tests, which means that this effect is still somehow internally considered in wind loads calculations to BS 6399-2.
- The ASCE 7-05 code bases its calculations for the basic wind speed on the 3 second gust speed, whereas the BS 6399-2 uses a mean hourly wind speed. Although these two values are quite different from each other, the corresponding wind loads out of these two codes are similar to each other, and not much affected by this difference in basic wind speed definition.
- The definition for gust factor in the ASCE 7-05 is a little bit complicated and depends on lots of variables including the building outer dimensions, dynamic properties, and wind characteristics, whereas in the BS 6399-2, it depends only on the building outer dimensions, and even uses a constant value for the hybrid combination method. Again these two values are quite different from each other, but does not much affect the overall loads.
- Although the stories forces may have noticeable differences between the studied methods, the overall effect of stories shears and overturning moments are always much less in the percentages of differences.

Some recommendations could be drawn from this research:

- Buildings of height range 200 – 300 m, number of stories 50 – 90 stories, and height to width or depth aspect ratios 1:4 – 1:8, are only considered in this study; other buildings ranges are required to be tested for the same criteria.
- Only the along and across winds are considered in this research, the torsion effects of wind loads on tall buildings should be tested
- A wider range of international codes and standards could be included such as: the Uniform Building Code (UBC), International Building Code (IBC), Euro Code (EURO), National Building Code of Canada (NBCC), Australian Code (AS/NZS), and the Chinese Code (CC).
- Comparing wind tunnel test results to numerical models using the computational fluid dynamic (CFD) method as well as results from the full scale measurements (FSM) for some case studies buildings.

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