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EVALUATION OF WIND EFFECTS ON BUILDINGS USING DESIGN CODES AND NUMERICAL WIND TUNNEL TESTS

OCENA WPŁYWU WIATRU NA BUDYNKI Z WYKORZYSTANIEM NORM PROJEKTOWYCH I TESTÓW NUMERYCZNYCH W METODZIE TUNELU AERODYNAMICZNEGO

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Abstract

The evaluation of wind effect on the regular shape and simple diaphragm buildings and structures due to wind load has been calculated by several international codes and standards where wind gust nature and dynamic effect could not capture. Bangladesh National Building Code (BNBC) provides the tools for engineers to calculate the wind pressures for the design of a regular-shaped structure with a height to width ratio of less than 5.0, a simple diaphragm, and no unusual geometrical irregularity. If these conditions do not satisfy a wind tunnel testing is required. In this study, a comparative study between two codes in Bangladesh (BNBC-2006 and BNBC-2020), and wind tunnel test results are conducted. An investigation is carried out on four typical buildings with variable heights located within Dhaka, Bangladesh. A computational fluid dynamics (CFD) program RWIND is used to calculate the wind loads on buildings and are compared with those obtained by Bangladesh National Building Codes. Storey shear of four different building models is compared. Between BNBC-2006 and BNBC-2020, there is up to a 53% difference in storey shear. Whereas, up to 30% variation in storey shear is observed between the numerical wind tunnel test data and the data calculated using the BNBC-2020 equations. Finally, this study will help in improving BNBC code provisions for wind load calculations.

Keywords: wind load analysis, wind tunnel test, wind simulation, reinforced cement concrete structure, computational fluid dynamics, Bangladesh National Building Code

Streszczenie

Kalkulację wpływu wiatru na budynki i budowle o regularnych kształtach i prostych konstrukcjach pod obciążeniem wiatrem przedstawiono w kilku normach międzynarodowych, w których jednak nie uwzględniono charakteru podmuchów wiatru i efektu dynamicznego. Bangladeska Krajowa Norma Budowlana (BNBC) zapewnia inżynierom narzędzia do obliczania ciśnienia wiatru przy projektowaniu konstrukcji o regularnym kształcie, o stosunku wysokości do szerokości mniejszym niż 5,0, prostej konstrukcji oraz bez nietypowych nieregularności geometrycznych. Jeśli warunki te nie są spełnione, wymagane jest przeprowadzenie testów w tunelu aerodynamicznym. W niniejszym opracowaniu przeprowadzono badanie porównawcze między dwiema normami obowiązującymi w Bangladeszu (BNBC-2006 i BNBC-2020) oraz wyni-

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kami testów w tunelu aerodynamicznym. Badanie przeprowadzono na czterech typowych budynkach o różnej wysokości zlokalizowanych w Dhace w Bangladeszu. Program RWIND do obliczeń i symulacji dynamiki płynów (CFD) został wykorzystany do obliczenia obciążeń wiatrem na budynkach i porównany z wynikami uzyskanymi według bangladeskich norm budowlanych. Porównano ścinanie kondygnacji czterech różnych modeli budynków. W tym względzie różnice pomiędzy BNBC-2006 i BNBC-2020 wynoszą do 53%. Natomiast między danymi z numerycznego testu w tunelu aerodynamicznym a danymi obliczonymi przy użyciu równań BNBC-2020 zaobserwowano do 30% różnic w odniesieniu do ścinania kondygnacji. Badanie to pomoże też ulepszyć przepisy norm BNBC dotyczące obliczeń obciążenia wiatrem.

Słowa kluczowe: analiza obciążenia wiatrem, test w tunelu aerodynamicznym, symulacja oddziaływania wiatru, konstrukcja żelbetowa, obliczeniowa dynamika płynów, bangladeska krajowa norma budowlana

1. INTRODUCTION

World population growth rapidly increasing day by day which leads to more demand for tall buildings, especially in countries where land is not sufficient because of the high population. For designing Civil Engineering structures there have three important design requirements: more service period, serviceability and people's safety. The present wind loads codes are based on constant values of pressure coefficients for the regular size and shape of structures. Irregular shapes of buildings and structures are not enlisted in those codes, for these types of structures wind load calculation and assess by wind tunnel tests (Fouad et al., 2018). However, these tests are not accessible for most designers due to higher cost and time requirements. There have also been some difficulties to imitate the full-scale Reynold's number (Barlow et al., 1999). In particular for tall buildings that are more vulnerable to wind forces, wind pressure coefficients (Cp) are significant numbers for building engineering applications, such as estimating wind loads or wind-induced air infiltration (Costola et al., 2009). Several factors, including building shape, the placement of the façade, exposure, and wind directions, affect wind pressure coefficients (Charisi et al., 2019).

Full-scale wind-tunnel measurements are thought to be the most accurate techniques for generating actual wind pressure coefficients (Irtaza et al., 2013). During full-scale measurements, it is not essential to replicate boundary conditions, apply physical models, or do any downscaling (Flay et al., 2013). On the other side, the user can precisely alter the approach flow for wind-tunnel measurements, including wind speed, direction, and turbulence (Allegrini et al., 2014). Full-scale measurements take a lot of work, money, and time to complete. Similar to this, wind tunnel measurements cost a lot of money and require much knowledge. Full-scale studies for assessing wind-induced pressures have previously been carried out in low-rise structures with simple shape (Blocken, 2014). Wind-tunnel tests are a valuable method for establishing wind pressure coefficients because full-scale data have been used to confirm reduced-scale measures, such as those employed in wind tunnel testing, and they have shown agreement (Blocken, 2014). The air fluxes are more accurately calculated using variable Cp values than they are using the standard approach, which uses mean Cp values (Charisi et al., 2019).

Advanced development of computer technology in the recent year in computational fluid dynamics (CFD) gains more advantages for a scaled model with boundary layer tests and becoming an efficient and reliable tool for wind load calculation (Raman et al., 2018). The CFD technique gives more detailed data for a wide range of boundary conditions within a short time and is more cost-effective in comparison to wind tunnel tests (Bendjebbas et al., 2016). The majority of numerical research refers to the basic cube form exposed to wind perpendicular to its face for testing and confirming the correctness of computational evaluations of wind pressures (Stathopoulos, 2002 and 2003). This is related to the cube's simple design, which includes key intricate parts of a real building flow, and the amount of full-scale and experimental results in the literature. Wright and Easom (2003) evaluated the mean pressure coefficient on the surface of the Silsoe cube using the standard k-ε model. However, very few studies have been reported on pressure coefficient calculations of a multi-storied reinforced concrete building using numerical wind tunnel tests.

1.1. Research Significance

Bangladesh National Building Code (BNBC) provides the tools for engineers to calculate the wind pressures for designing the regular-shaped building. Where regular-shaped building properties are defined as (i) building height to minimum lateral dimension ratio not more than 5.0, (ii) building natural frequency in the first mode is equal or more than 1 Hz, (iii) simple diaphragm, and no unusual geometrical irregularity, etc. (BNBC, 2006). Significant modifications of wind load calculation have been suggested in the new building design code BNBC-2020 compared to the previous code BNBC-2006. However, the code does not consider the uneven effects (turbulence, torsional effect, etc.) on the building due to a cross-wind, vortex shedding, and instability for galloping or flutter. Furthermore, special consideration is required for channeling impacts in the wake of upwind obstructions (BNBC, 2020). Calculation of wind load is critical for tall, unusually shaped buildings or buildings located in hurricane-prone areas. The BNBC-2020 recommends performing a wind tunnel test. Wind tunnel testing provides more accurate design information, but it is expensive and time-consuming (Soligo, 2019). Alternatively, numerical simulation of the wind tunnel is an easy and effective tool for engineers to evaluate the design information of the concerned building (Daemei, 2019). Therefore, the present study will help the engineering community to adopt a numerical wind tunnel approach for the design of irregular and high-rise building structures.

1.2. Model Verification

For verification, wind tunnel test results of the Commonwealth Advisory Aeronautical Council (CAARC) building are compared with numerical wind simulation program. The geometrical modelling for the numerical simulation of the CAARC building model was built in a 1:400 scale rigid model, for wind tunnel testing. The building model is rectangular with dimensions of 100.0 ft parallel to the wind, 150.0 ft perpendicular to the wind, and 600.0 ft in height. For the numerical wind tunnel test, the wind tunnel dimensions are 4950.0 ft in the windward direction and 3000.0 ft in the spanwise direction, and the total height is twitching the model size equal to 1200.0 ft. The velocity profile for numerical wind tunnel test in CFD simulation takes the following power-law as equation 1 is exponent of 0.16 for verification test results (Juretić et al., 2013):

$$V_z = V_g \left(\frac{z}{z_g} \right)^{\alpha} \tag{1}$$

The simulation results show a close comparison with the experimental results according to the wind tunnel test on the windward face shown in Figure 1. However, for the sidewall and leeward faces, up to 15% variation between the measured and the calculated data are observed. The differences mainly depend on the boundary mesh and turbulence model.

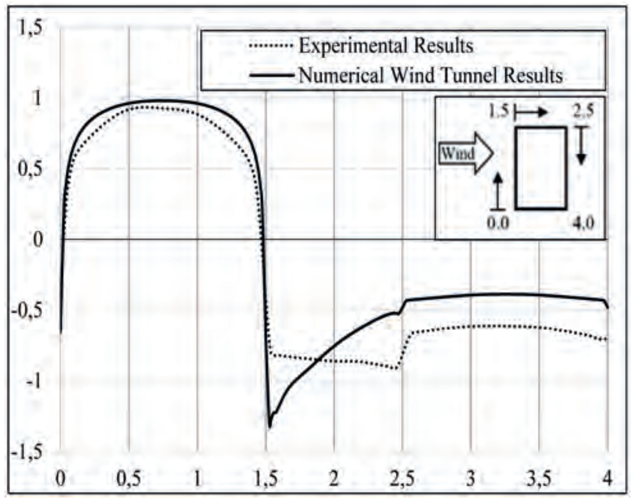

Figure 1. Values of Mean Pressure Coefficients (Cp) over the Perimeter at 2H/3

2. METHODOLOGY

Comparisons are performed with respect to storey shear between the BNBC code values and numerical wind tunnel test data. A numerical wind tunnel test is performed in RWIND shown in Figure 2, which gives the wind pressure coefficients at windward, leeward and side surfaces. The pressure coefficients at 3 and 7 feet of each storey are extracted, and the arithmetic means value for each storey for each vertical panel is calculated.

All the building models are modelled in ETABS, commercial building analysis and design software. Pressure coefficients calculated from the RWIND are assigned to the windward, leeward and two sides surfaces as shown in Figure 3. On each floor, all surface is divided vertically into a number of panels. For each panel pressure coefficient input is given in ETABS. Two sets of pressure coefficients are calculated following the two sets of velocity profiles suggested by BNBC-2006 and BNBC-2020.

On the other hand, constant pressure coefficients are provided on the windward, leeward, and two sides following the BNBC-2006 and BNBC-2020. For analysis purposes, standard dead and live loads are incorporated in ETABS. However, no earthquake load is considered. Concrete compressive strength, reinforcement yield strength, beam and column size are considered as per Table 1. The slab thickness is 150 mm. Analysis of the building structure is performed in ETABS and storey shear is calculated for each storey of the building.

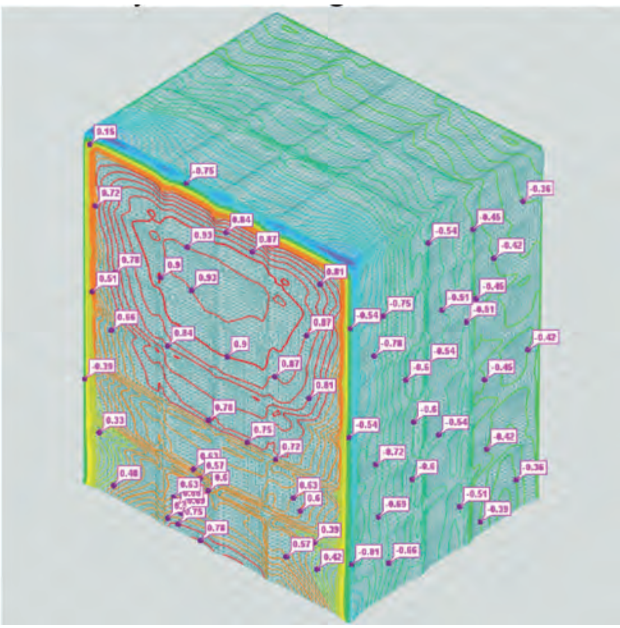

Figure 2. Contours of Cp in the numerical wind tunnel test

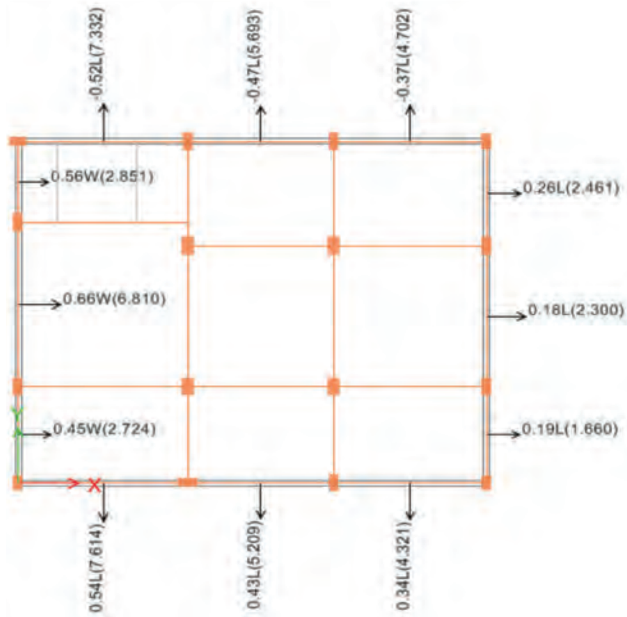

Figure 3. Pressure Coefficient (Cp) is added in ETABS for Analysis

2.1. Building Models

Four reinforced concrete buildings are considered in this study as described in Table 1. Model-01 is a six-storey, Model-02 is a ten-storey, Model-03 is a twenty-storey, and Model-04 is a forty-storey reinforced concrete building and the building geometry considerd as shown in Figure 4. The exposure (terrain) categories applied in this study are A&B according to BNBC-2006 and BNBC-2020 and the buildings are considerd in Dhaka, Bangladesh. For simplicity, the effects of the wind direction, topography, shielding, importance factor, and return period are not considered in the following discussion.

Table 1. Building models

Description	Model-01 (six-storey)	Model-02 (ten-storey)	Model-03 (twenty-storey)	Model-04 (forty-storey)
Plan, B x L [m]	12 x 15	15 x 23	24 x 42	24 x 36
Height, H [m]	18.91	30.05	61.61	122
Storey Height [m]	Ground Floor – 3.66 Typical Floor – 3.05	Ground Floor – 3.05 Typical Floor – 3.05	Ground Floor – 3.66 Typical Floor – 3.05	Ground Floor – 3.05 Typical Floor – 3.05
Materials (ksi)	$f'_c = 3, f_y = 60$	$f'_c = 4, f_y = 60$	$f'_c = 4, f_y = 60$	$f'_c = 4, f_y = 60$
Exposer Category	B	A	A	A
Structure Type	RC Frame Structure	RC Frame Structure	RC Frame Structure	RC Frame Structure
Length-to-width ratio	1.250	1.500	1.795	1.500
Height-to-width ratio	1.550	2.000	2.590	5.000
Corner Columns [mm]	300 x 525	375 x 500	375 x 875	625 x 875
Edge Columns [mm]	300 x 600	375 x 625	375 x 1000	750 x 1000
Central Columns [mm]	375 x 600	500 x 600	500 x 1250	625 x 1250
Beams [mm]	250 x 375	300 x 500	300 x 750	300 x 750

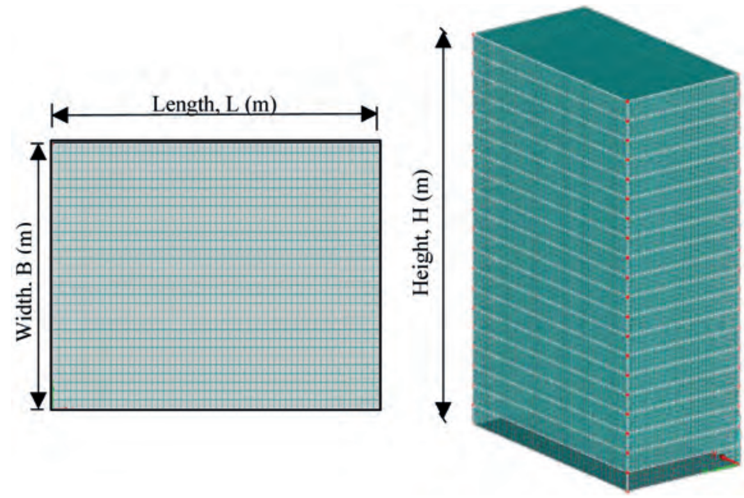

Figure 4. Typical Building Geometry

3. RESULTS AND DISCUSSION

In this study, storey shears for four different reinforced concrete buildings with various numbers of storeys, such as six-storied, ten-storied, twenty-storied and forty-storied, are compared. Building model information is presented in Section 2. Storey shears following BNBC-2006 and BNBC-2020 are calculated using ETABS.

3.1. Model-01 (six-storied structure)

The comparison of the storey shear in the long and short directions for the six-storied building can be seen in Figure 5. For the first storey, the storey shear increased with an increase in height. Above that, the storey shear decreased gradually with an increase in height. Furthermore, BNBC-2020 and BNBC-2006 showed a considerable variation in calculating the storey shear. The storey-wise variation ranged from 50.0% to 53.5% with a mean variation of 51.4% in the long direction, while the variation range was 45.7% to 49.4% with a mean variation of 47.1% in the short direction.

The variation in storey shear for the numerical wind tunnel test (NWTT) using the BNBC-2020 velocity profile and BNBC-2020 manual is smaller compared to the variation in storey shear for the NWTT using the BNBC-2006 velocity profile and BNBC-2006 manual. Storey-wise variation of storey shear between the NWTT of BNBC 2020 with the BNBC-2020 manual calculation ranged from 15.3%

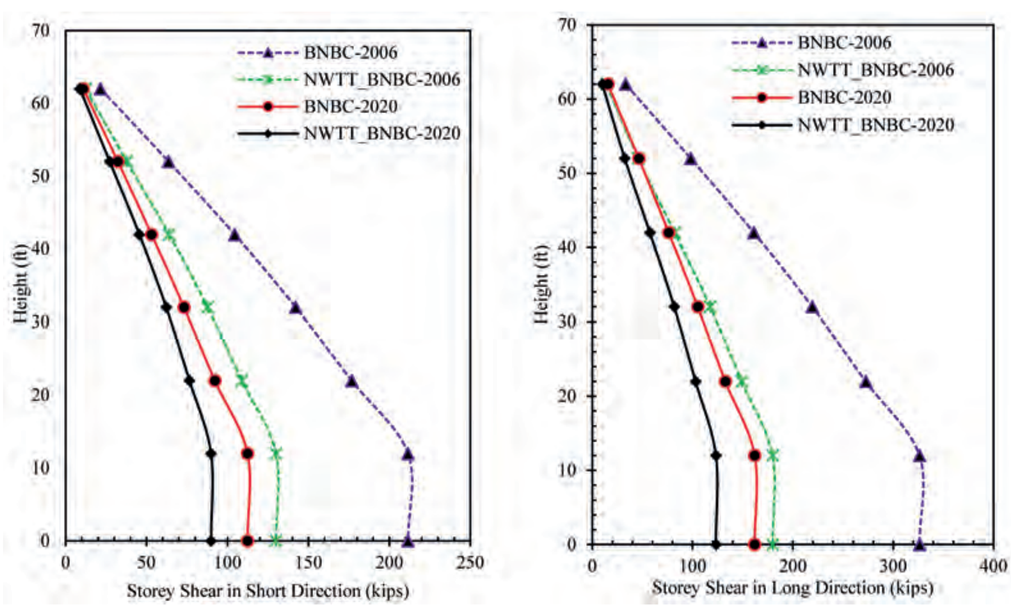

Figure 5. Storey shear along the short and long directions for model-01 (six-storied structure)

to 25.6% in the long direction with a mean of 19.5%, and 12.8% to 22.5% with a mean of 16.7% in the short direction. While the variation between the NWTT of BNBC 2006 with the BNBC-2006 manual calculation ranged from 40.9% to 45.3% in the long direction with a mean of 43.1%, and 33.8% to 38.4% with a mean of 36.2% in the short direction.

3.2. Model-02 (ten-storied structure)

The comparison of the storey shear in both directions of the ten-storied building can be seen in Figure 6. For the first storey, the storey shear increased with an increase in height. Above that, the storey shear decreased gradually with an increase in height. As observed in Figure 8, BNBC-2020 and BNBC-2006 showed significant fluctuations in calculating the storey shear. The storey-wise variation ranged from 43.6% to 51.6% with a mean variation of 47.2% in the long direction, while the variation range was 32.9% to 41.8% with a mean variation of 36.9% in the short direction.

The NWTT using the BNBC-2020 velocity profile showed relatively small fluctuations with the BNBC-2020 manual compared to the fluctuations observed between the storey shear for the NWTT with the BNBC-2006 velocity profile and the BNBC-2006 manual. Storey-wise variation of shear force between the NWTT of BNBC-2020 with the BNBC-2020 manual, ranged from 22.2% to 34.6% in the long direction with a mean of 28.3%, and 26.9% to 37.7% with a mean of 31.6% in the short direction. While the variation between the NWTT of BNBC 2006 with the BNBC-2006 manual, ranged from 49.4% to 58.1% in the long direction with a mean of 52.5% and 44.0% to 49.7% with a mean of 46.55 in the short direction.

3.3. Model-03 (twenty-storied structure)

The storey shear in short and long directions for a twenty-storied typical reinforced concrete building is displayed in Figure 7. Overall, the storey shear decreases with an increase in height. As observed from the figure, BNBC-2020 and BNBC-2006 showed a considerable variation in calculating the storey shear. The storey-wise variation ranged from 45.9% to 60% with a mean variation of 52.3% in the long direction, while the variation ranged from 36.5% to 52.1% with a mean variation of 43.4% in the short direction. The NWTT using the BNBC-2020 velocity profile showed a relatively small variation with the BNBC-2020 manual in comparison to the variation from the NWTT using the BNBC-2006 profile and the BNBC-2006 manual.

Storey-wise variation of wind pressure coefficient between the NWTT with BNBC-2020 with the BNBC-2020 manual, ranged from 23.6% to 40.1% in the long direction with a mean of 30.1%, and 27.5% to 42.9% with a mean of 33.4% in the short direction. On the other hand, the variation between the NWTT with BNBC-2006 with the BNBC-2006 manual, ranged from 51.4% to 64.4% percent in the long direction with a mean of 54.0%, and 48.4% to 60.3% with a mean of 50.7% in the short direction.

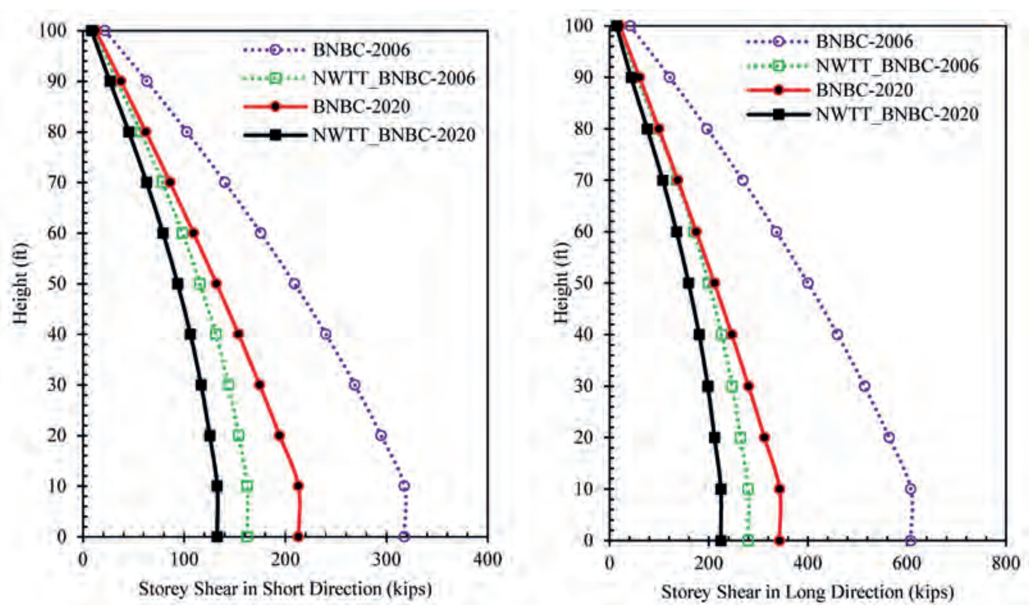

Figure 6. Storey shear variation in the short and long directions for model-02 (ten-storied structure)

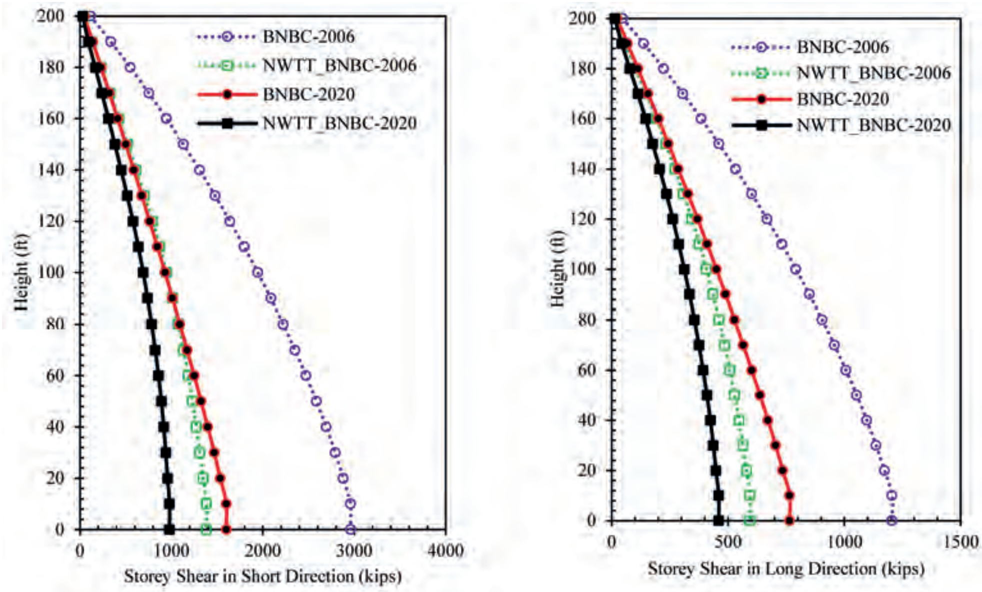

Figure 7. Storey shear along short and long directions for model-03 (twenty-storied structure)

3.4. Model-04 (forty-storied structure)

The storey shear in short and long directions of a typical forty-storied structure is seen in Figure 8. In general, the storey shear decreases with an increase in height. The BNBC-2020 and BNBC-2006 showed a considerable variation in calculating the storey shear. The storey-wise variation ranged from 50.0% to 56.9% with a mean variation of 54.0% in the long direction, while the variation ranged from 35.2% to 43.5% with a mean variation of 40.0% in the short direction.

The NWTT using the BNBC-2020 velocity profile showed a relatively small variation with the BNBC-2020 manual in comparison to the variation from NWTT using the BNBC-2006 velocity profile with the BNBC-2006 manual. Storey-wise variation of storey shear between the NWTT of BNBC-2020 with the BNBC-2020 manual, ranged from 22.4% to 47.5% in the long direction with a mean of 28.9%, and 22.0% to 43.5% with a mean of 40.0% in the short direction. Furthermore, the variation between the NWTT of BNBC-2006 with the BNBC-2006

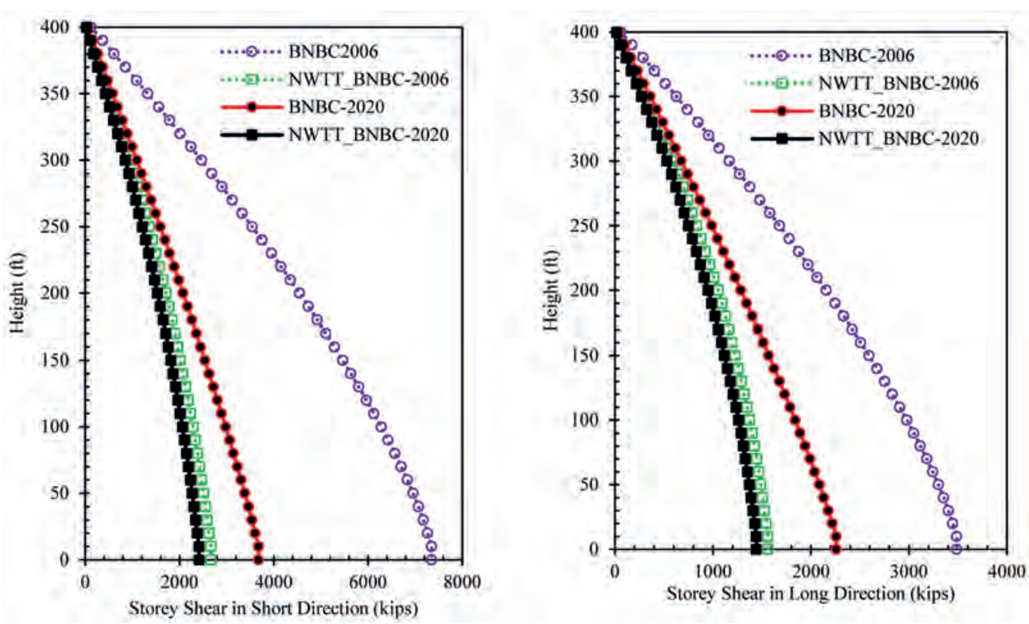

Figure 8. Storey shear along short and long direction for model-04 (forty-storied structure)

manual ranged from 60.9% to 74.2% in the long direction with a mean of 63.5% and 48.9% to 64.8% with a mean of 52.9% in the short direction.

4. CONCLUSIONS

In the present study, storey shear for four different heights of buildings was compared while using wind pressure coefficient from BNBC-2006 and BNBC-2020, and numerical wind tunnel test (NWTT). The summary of the findings is presented here.

1. The NWTT can forecast the results of wind tunnel experiments. Experimental and numerical wind tunnel test data are quite close on the windward face. However, up to 15% variance is recorded on the leeward and side faces.
2. BNBC-2020, NWTT (BNBC-2020), and NWTT (BNBC-2006) showed relatively similar story shear for all the models, however, the BNBC-2006 showed higher than among all. Analysis of the four different storied structures reveals that BNBC-2006 give up to 60% (around) higher storey shear compared to the BNBC-2020. The average variation of story shear among the BNBC-2020, NWTT (BNBC-2020), and NWTT (BNBC-2006) are around 12%.
3. The present study reveals that BNBC-2006 overestimates the storey share by 1.4 times. Therefore, it may be of interest for the designer to adopt a numerical wind tunnel test for the high-rise building wind load analysis or should stict to the BNBC 2020 atleast, rather than using the fixed wind load coefficient proposed by the code BNBC 2006, which is the older version.

REFERENCES

[1] Abdi D.S., Bitsuamlak, G.T., (2016), *Wind flow simulations in idealized and real built environments with models of various level of complexity*. Wind and Structures, 22(4), 503-524. https://doi.org/10.12989/was.2016.22.4.503.

[2] Abdullah F., Islam Z., Asif M.A.T., Ali S., (2021), *A Comparative Study of Lateral Load Analysis Considering Two BNBC Codes Using ETABS Software*, American Journal of Civil Engineering, 9(4), 118-126, https://doi.org/10.11648/j.ajce.20210904.13.

[3] Allegrini J., Dorer V., Carmeliet J., (2014), *Buoyant flows in street canyons: Validation of CFD simulations with wind tunnel measurements*, Building and Environment, 72, 63-74. https://doi.org/10.1016/j.buildenv.2013.10.021.

[4] ASCE/SEI 7-10. (2010), Minimum design loads for buildings and other structures. In American Society of Civil Engineers.

[5] Bangladesh National Building Code, BNBC, 2006, Housing and Building Research Institute and Bangladesh Standard and Testing Institute, Bangladesh.

[6] Bangladesh National Building Code, BNBC, 2020, Housing and Building Research Institute and Bangladesh Standard and Testing Institute, Bangladesh.

[7] Barlow J.B., Rae W.H., Pope A., (1999), *Low-speed wind tunnel testing*. John Wiley & Sons.

[8] Bendjebbas H., Abdellah-ElHadj A., Abbas M., (2016), *Full-scale, wind tunnel and CFD analysis methods of wind loads on heliostats: A review*. Renewable and Sustainable Energy Reviews, 54, 452-472, https://doi.org/10.1016/j.rser.2015.10.031.

[9] Braun A.L., Awruch A.M., (2009), *Aerodynamic and aeroelastic analyses on the CAARC standard tall building model using numerical simulation*, Computers & Structures, 87(9-10), 564-581, https://doi.org/10.1016/j.compstruc.2009.02.002.

[10] Charisi S., Thiis T.K., Aurlien T., (2019), *Full-scale measurements of wind-pressure coefficients in twin medium-rise buildings*, Buildings, 9(3), 63, https://doi.org/10.3390/buildings9030063.

[11] Computers and Structures Inc., (2022). ETABS Integrated Software for Structural Analysis and Design. [Online] Available: https://www.csiamerica.com/products/etabs. [10 January 2022].

[12] Costola D., Blocken B., Hensen J.L.M., (2009), *Overview of pressure coefficient data in building energy simulation and airflow network programs*, Building and Environment, 44(10), 2027-2036, https://doi.org/10.1016/j.buildenv.2009.02.006.

[13] Dlubal Software GmbH, (2022), RWIND Simulation, Wind Simulation (Wind Tunnel), [Online] Available: https://www.dlubal.com/en/products/stand-alone-structural-analysis-software/rwind-simulation. [6 March 2022].

[14] Douvi C.E., Tsavalos I.A., Margaris P.D., (2012), E*valuation of the turbulence models for the simulation of the flow over a National Advisory Committee for Aeronautics (NACA) 0012 airfoil*. Journal of Mechanical Engineering Research, 4(3), 100-111. https://doi.org/10.5897/jmer11.074.

[15] El-Behery S.M., Hamed M.H., (2011), *A comparative study of turbulence models performance for separating flow in a planar asymmetric diffuser*. Computers & Fluids, 44(1), 248-257, https://doi.org/10.1016/j.compfluid.2011.01.009.

[16] Flay R.G., Carpenter P., Revell, M., Cenek, P., Turner, R., King, A., (2013), *Full-scale wind engineering measurements in New Zealand*, In The 8th Asia-Pacific conference on wind engineering, (pp. 10-14), https://doi.org/10.3850/978-981-07-8012-8_key-09.

[17] Fouad N.S., Mahmoud G.H., Nasr N.E., (2018), *Comparative study of international codes wind loads and CFD results for low rise buildings*. Alexandria Engineering Journal, 57(4), 3623-3639, https://doi.org/10.1016/j.aej.2017.11.023

[18] Hasan M., Debnath S., Akther A., (2022), *Comparative Study of Lateral Loads and Its Cost Effect on RC* Moment Frame and Wall-frame Building According to BNBC 2020 in Different Zones of Bangladesh.

[19] Irtaza H., Beale R.G., Godley M.H.R., Jameel A., (2013), *Comparison of wind pressure measurements on Silsoe experimental building from full-scale observation, wind-tunnel experiments and various CFD techniques*. International Journal of Engineering, Science and Technology, 5(1), 28-41, https://doi.org/10.4314/ijest.v5i1.3.

[20] Juretić F., Kozmar H., (2013), *Computational modeling of the neutrally stratified atmospheric boundary layer flow using the standard k–ε turbulence model,* Journal of Wind Engineering and Industrial Aerodynamics, 115, 112-120, https://doi.org/10.1016/j.jweia.2013.01.011.

[21] Liu Z., Chen J., Xia Y., Zheng Y., (2021), *Automatic sizing functions for unstructured mesh generation revisited.* Engineering Computations, https://doi.org/10.1108/ec-12-2020-0700.

[22] Tan H., Pillai K.M., (2009), *Finite element implementation of stress-jump and stress-continuity conditions at porous-medium, clear-fluid interface*. Computers & Fluids, 38(6), 1118-1131, https://doi.org/10.1016/j.compfluid.2008.11.006.

[23] Vino G., Watkins S., Mousley P., Watmuff J., Prasad S., (2005), *Flow structures in the near-wake of the Ahmed model*. Journal of Fluids and Structures, 20(5), 673-695, https://doi.org/10.1016/j.jfluidstructs.2005.03.006.

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