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Chicago Building Code Modernization: Comparison of Prototype Building Designs


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Abstract

This research paper, an abridged version of a white paper produced by the Chicago Chapter of the Council on Tall Buildings and Urban Habitat (CTBUH), reviews the potential impact of changes to the city's building code as it is adapted to the International Building Code standard. Its main objective is to uncover the effect of IBC loading standards on the structural designs of a range of taller buildings in Chicago that may utilize prescriptive code design methodology, to assess the cost implications of a change in loading standards, and to assess the effect of IBC's seismic loading requirements on representative local building projects.

Keywords: Chicago Building Code, International Building Code, Structural Engineering, Tall Buildings

Background

For many years, local design and construction industries understood there was a need to better align Chicago's Building Code (CBC) with more modern codes and standards used throughout the US. Through collaboration with many departments within the City of Chicago, the Mayor's Office, and more than 150 volunteer technical experts and industry leaders, the Chicago Building Code was comprehensively revised in 2019. The revised structural requirements are based upon the International Building Code (IBC)—the modern national standard, while maintaining and introducing special Chicago-specific provisions.

As part of the new code adoption process, projects filed between 1 December 2019 and 1 August 2020 will have the option of using a design methodology based on the original (pre-2019) CBC or the new 2019 CBC, which references the 2018 IBC. After 1 August 2020, all new designs submitted for approval will need to conform to the new 2019 CBC.

Study Objective and Scope

Structural engineers familiar with the CBC and IBC recognize that design lateral forces developed by the two codes can vary significantly. Low-rise buildings may realize a reduction in wind loads with the IBC, but as a building gets taller and the exposure category increases (as specified by ASCE 7 Exposure Category B to D), wind loads can significantly increase. Additionally, the IBC requires that designs consider seismic loading, so heavier low-rise buildings may also see an increase in demand from new code loading.

The study presented in this paper attempts to answer the following questions:

- How does the IBC loading affect the structural designs of a range of taller buildings in Chicago that may utilize prescriptive code design methodology?
- How significant is the impact to structural cost?
- How does seismic loading impact these sample building designs?

In order to gain insight into these questions, three prototype buildings were analyzed and designed according to both CBC and IBC. The prototype buildings considered do not represent the full range of Chicago's building stock, but are representative of the building types that are less than 400 feet (122 meters) tall, and as a result can utilize prescriptive code provisions for design (i.e. no wind tunnel testing). Additionally, a low-rise reinforced concrete office building is also considered for study, since short and heavier buildings are more susceptible to seismic loading.

The three prototype buildings examined as part of this research paper are shown in figures 1 and 2 and a detailed description of each is provided below.

> "The Chicago Wind Climate model suggests that wind loading from the easterly winds is expected to be significantly lower than prevailing strong winds from south and west."

Prototype Building 1

Prototype Building 1 is a residential tower with a 15-foot, 8-inch (4.8-meter) ground floor lobby and 36 floors at a 10-foot, 8-inch (3.3-meter) floor-to-floor height. The building roof has an elevation of 399 feet, 8 inches (121.8 meters) (see Figure 1), just below the 400-foot (121.9-meter) threshold requirement for wind tunnel testing per IBC.

The floor plate is 100 feet (30.5 meters) square, with columns around the perimeter spaced at 30 feet (9.1 meters) on center (see Figure 2). Elevated floors are 8-inch-(203-millimeter)-thick post-tensioned concrete slabs. The lateral system consists of a concrete bearing shear wall core with dimensions of 44 feet, 9 inches (13.6 meters) and 30 feet (9.1 meters). The core has web walls at the elevator and stairs that are 10 inches (254 millimeters) thick and are included in the analysis model. Concrete link beams at the core wall door rough openings are 29 inches (737 millimeters) deep and match the thickness of the shear walls. This corresponds to a door opening height of 8 feet, 3 inches (2,514 millimeters). Widths used for the door rough openings are 4 feet (1,219 millimeters) for single doors, and 8 feet (2,438 millimeters) for double doors.

Prototype Building 2

Prototype Building 2 is an office building with a 20-foot (6.1-meter) ground floor lobby and 19 floors at a 14-foot (4.3-meter) floor-to-floor height. The building roof has an elevation of 286 feet (87.2 meters) (see Figure 1). An exterior windscreen extends an additional 14 feet (4.3 meters) forming a mechanical penthouse for a total building height of 300 feet (91.4 meters) above grade.

The floor plate is 180 feet by 130 feet (54.9 meters by 39.6 meters). Columns are spaced on a 30-foot (9.1-meter) grid in the longitudinal direction with 45-foot (13.7-meter) lease spans on each side of an interior 40-foot (12.2-meter) bay (see Figure 2). The floor system consists of 3-1/4-inch (83-millimeter) lightweight concrete on a 3-inch (76.20-millimeter) metal deck supported by structural steel infill framing at 15 feet (4.6 meters) on center. The lateral system consists of a concrete bearing shear-wall two-bay core, centered in the building with overall dimensions of 60 by 40 feet (18.3 by 12.2 meters). Concrete link beams at the core wall door openings are 36 inches (914 millimeters) deep and match the thickness of the shear walls. This corresponds to a door rough opening height of 11 feet (3,353 millimeters). Widths used for the door rough openings are 8 feet (2,438 millimeters).

Prototype Building 3

Prototype Building 3 is an office building with a 20-foot- (6.1-meter)-high ground floor lobby and 9 floors at a 14-foot (4.3-meter) floor-to-floor height. The building roof has an elevation of 146 feet (44.5 meters) (see Figure 1).

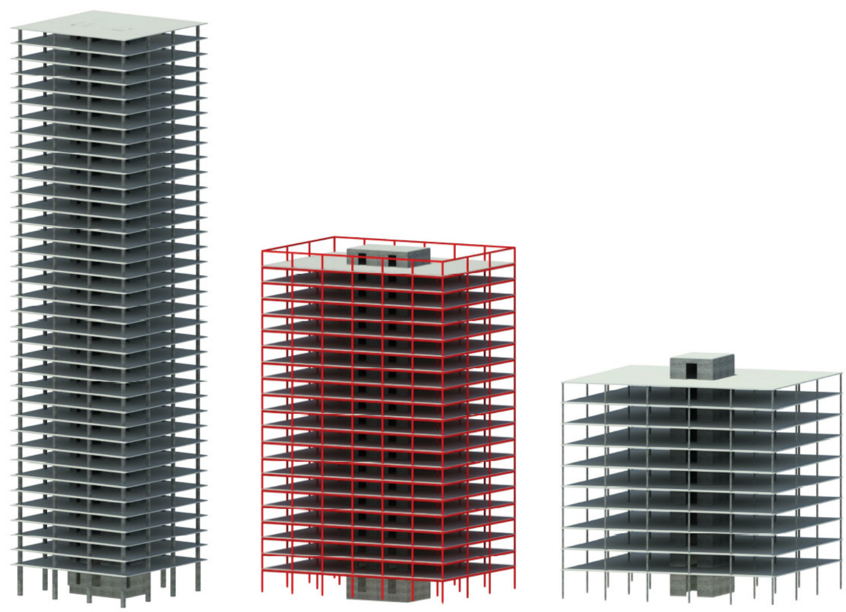


Figure 1. Isometric view of the prototype buildings.

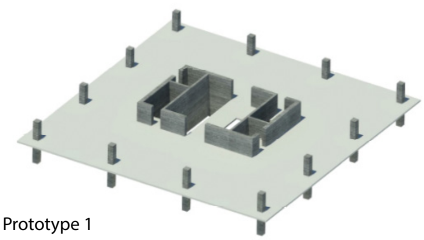
An exterior windscreen extends an additional 14 feet (4.3 meters), forming a mechanical penthouse for a total building height of 160 feet (48.8 meters) above grade.

The floor plate is 150 by 130 feet (45.7 by 39.6 meters). Columns are spaced in 30-foot (9.1-meter) grids in the longitudinal direction with 45-foot (13.7-meter) lease spans each side of an interior 40-foot (12.2-meter) bay (see Figure 2). The floor system consists of an 8-inch (203-millimeter) one-way concrete slab spanning 30 feet (9.1 meters) between concrete girders measuring 5 feet (1,524 millimeters) wide by 2 feet (610 millimeters) deep at column lines. The lateral system consists of a concrete bearing shear-wall single-bay core, centered in the building with overall dimensions of 30 feet (9.1 meters) by 40 feet (12.2 meters). Concrete link beams at the core wall door openings are 36 inches (914 millimeters) deep and match the thickness of the shear walls. This corresponds to a door rough opening height of 11 feet (3,353 millimeters). The width used for the door rough openings is 8 feet (2,438 millimeters).

Wind Loads

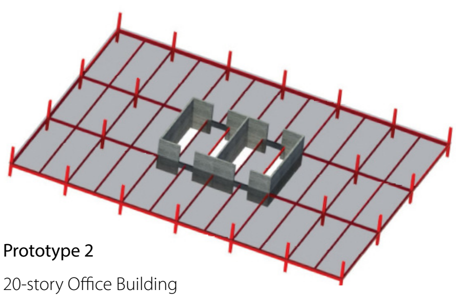
Applied wind loads can vary significantly between the CBC and IBC. CBC wind loads are based on a basic wind speed of 75 miles per hour defined as the Annual Extreme Fastest-Mile Speed, Ten Meters Above Ground. The design wind pressures for the CBC are prescriptively given in Table 13-52-310. These pressures do not account for exposure or the dynamic properties of the building.

For IBC wind loads, code-prescribed parameters are used in calculating the wind



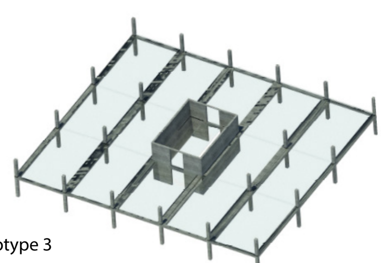
Prototype 1

37-story Residential Tower
100 x 100 feet
(30.5 x 30.5 meters)



Prototype 2

20-story Office Building
180 x 130 feet
(54.9 x 39.6 meters)



Prototype 3

10-story Office Building
150 x 130 feet
(45.7 x 39.6 meters)

Figure 2. Isometric view of floor plates of each prototype building.

Parameter	Value	Code Reference
Risk Category	II	IBC, Table 1604.5
Wind Importance Factor, I_w	1.00	ASCE 7-16, Table 1.5-2
Exposure Category	B or D	IBC, §1609.4
Basic Design Wind Speed, V	107 mph (47.8 m/s)	IBC, §1609.3
50 Year MRI Wind Speed for Drift	88 mph (39.3 m/s)	ASCE 7-16, Figure CC.2-3
Building Enclosure	Enclosed	
Internal Pressure Coefficient GC_{pi}	+/- 0.18	ASCE 7-16, Table 26.13-1

Table 1. Wind design parameters for the three prototype structures.

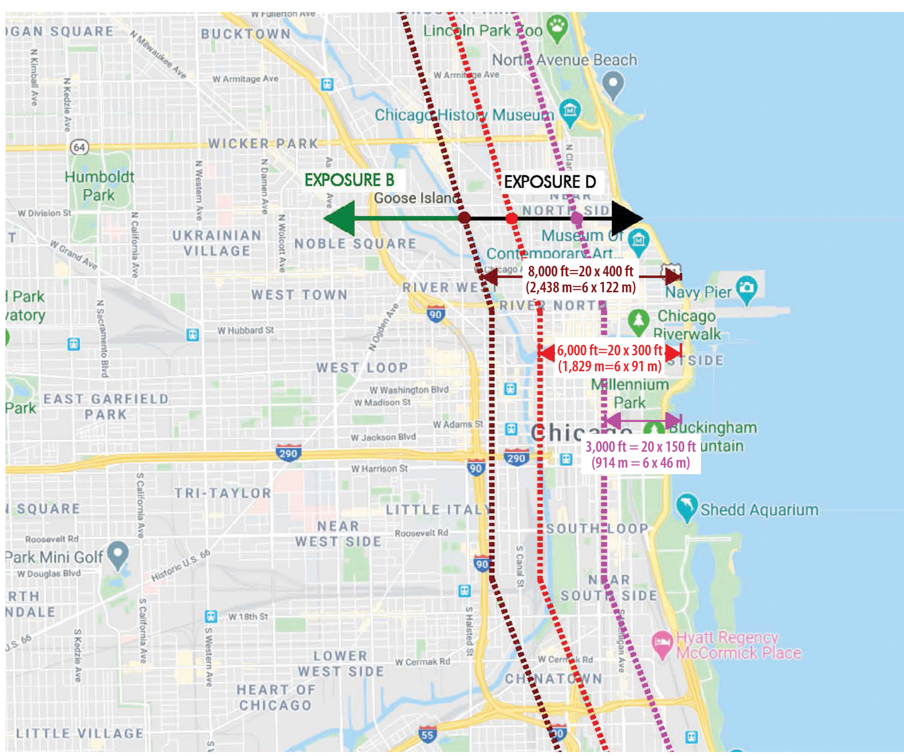


Figure 3. Chicago wind exposure levels.

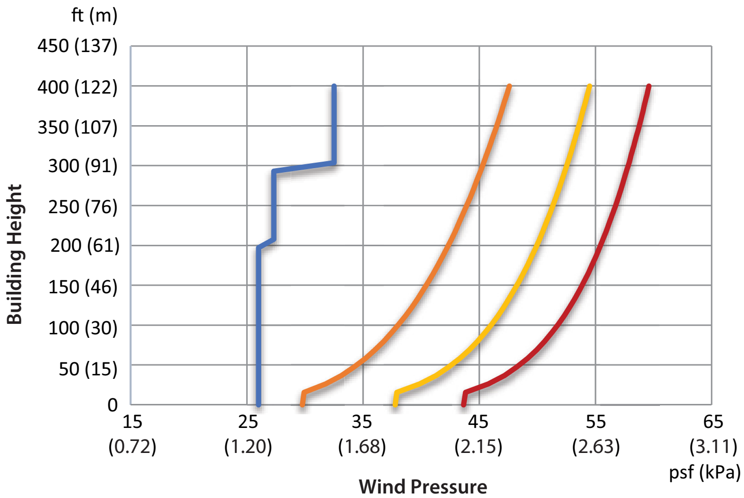


Figure 4. Strength design wind pressures for Prototype Building 1.

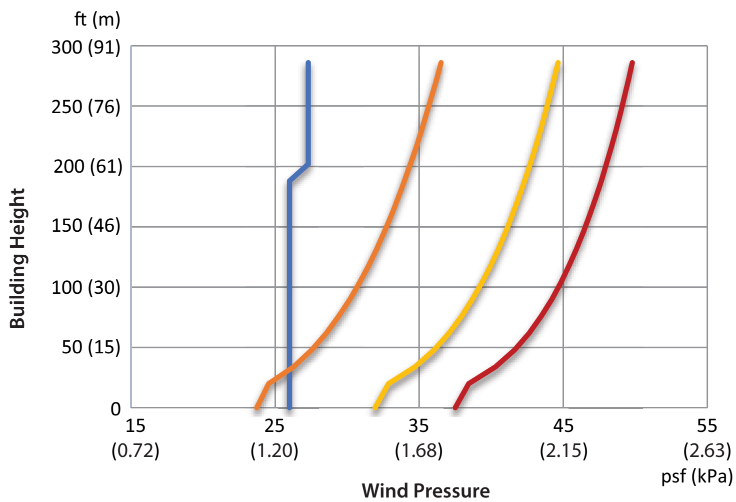


Figure 5. Strength design wind pressures for Prototype Building 2.

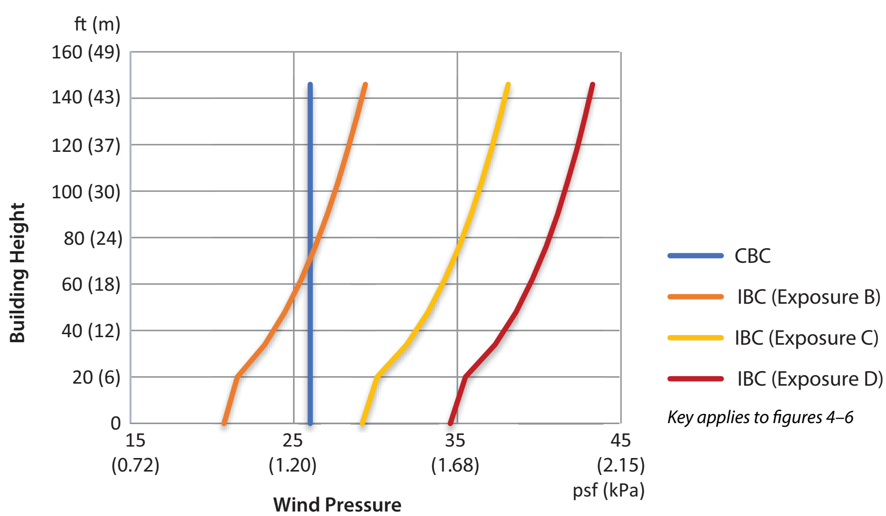


Figure 6. Strength design wind pressures for Prototype Building 3.

loads applicable to the main wind force resisting system (MWFRS), as shown in Table 1. The basic design wind speed is for a nominal design 3-second wind speeds at 33 feet (10 meters) above ground. The MWFRS in each direction is designed for the load cases as defined in ASCE 7-16.

Figure 3 plots the design wind exposures to which the model buildings were subjected. Figures 4, 5 and 6 provide comparisons of the CBC wind to the IBC wind for exposures B, C and D for prototype buildings 1, 2 and 3. Note that for the strength graphs in figures 5 and 6, the CBC wind pressures include a factor of 1.3 (directionality effects included) to make them comparable to IBC ultimate wind pressures.

Although the Wind Exposure D creates higher loading, the Chicago Wind Climate model (see Figure 7) suggests that wind loading from the easterly winds is expected to be significantly lower than prevailing strong winds from south and west.

Seismic Loads

Chicago has been exempt from seismic loads per the CBC prior to the incorporation of IBC. For the IBC, structures shall be designed and constructed to resist the effects of

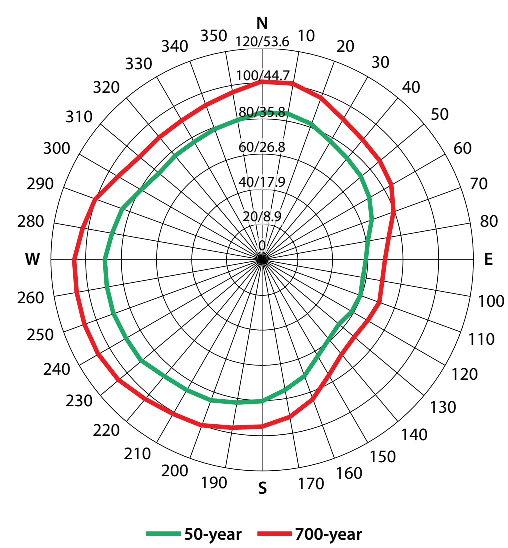


Figure 7. Chicago design wind speeds (mph/ mps).

> “The seismic parameters are based on the code-prescribed requirements and a representative Chicago West Loop geotechnical profile.”

earthquake motions. The parameters specified in Table 2 are utilized based on the code-prescribed requirements and a representative Chicago West Loop geotechnical profile.

The response spectrum is scaled in the ETABS structural model to 100 percent of the calculated base shear per ASCE 7-16, 12.9.1.4 (see Figure 8). The modal parameters and coefficients used to calculate the base shear are provided in Table 3.

Prototype Shear Wall Design Thicknesses

Walls are sized to achieve code compliance and maintain reasonable levels of reinforcement. Table 4 summarizes the core wall thicknesses.

Story Shears and Overturning Moments

The story shears and overturning moments for the prototype building designs are shown in the following figures. Wind loads govern over seismic loads for two of the design cases. However, for Prototype Building 3, seismic load in the Y-direction controls over the wind load for every exposure category except category D. Figures 9, 10, and 12 show the story shear (strength level) for each prototype building. Figures 9, 11, and 13 show the overturning moment (strength level) for each prototype building. As shown

Parameter	Value	Code Reference
Risk Category	II	IBC, Table 1604.5
Seismic Importance Factor, I_e	1.00	ASCE 7-16, Table 1.5-2
Seismic Design Category	B	IBC, Table 1613.2.3
S_{DS}	0.133g (1.3 m/s²)	IBC, Table 1613.2.3
S_{D1}	0.103g (1.01 m/s²)	IBC, Table 1613.2.3
Site Class	D	IBC, Section 1613.2.2
Lateral System Description		Bearing Wall System: Ordinary Reinforced Concrete Shear Walls - ASCE 7-16, Table 12.2-1
Seismic Response Coefficient, C_S		See Table 19.
Response Modification Factor, R	4	ASCE 7-16, Table 12.2-1
Deflection Amplification Factor, C_d	4	ASCE 7-16, Table 12.2-1
Redundancy Factor, ρ	1.0	ASCE 7-16, §12.3.4
Analytical Procedure		Modal Response Spectrum Analysis -ASCE 7-16, §12.9.1

Table 2. Seismic design parameters for the three prototype structures.

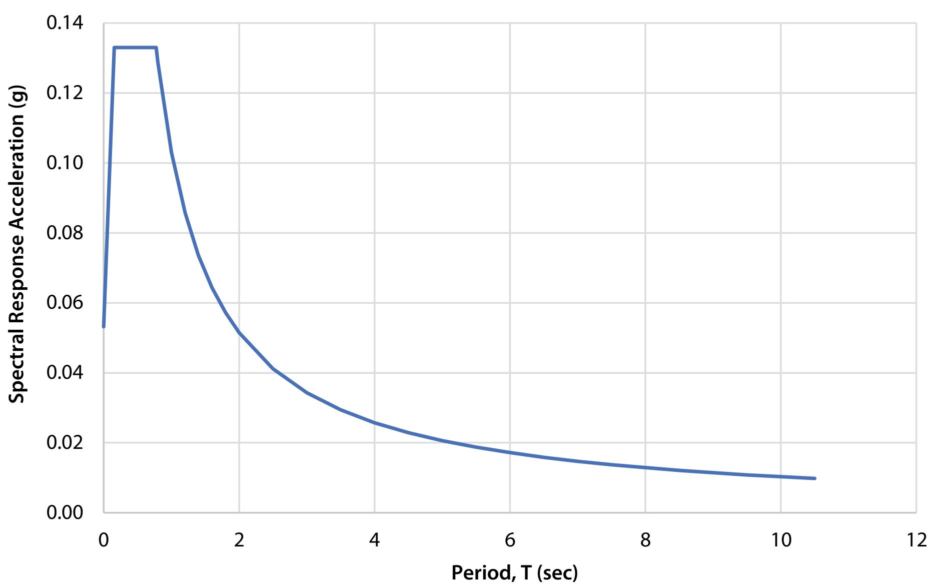


Figure 8. Design response spectrum curve for Site Class D developed for prototype buildings per ASCE 7-16.

	Prototype 1 37-story Residential Tower	Prototype 2 20-story Office Building	Prototype 3 10-story Office Building
Fundamental Mode Periods from Modal Analysis	Mode X = 3.6 s Mode Y = 4.4 s	Mode X = 1.91 s Mode Y = 1.84 s	Mode X = 1.57 s Mode Y = 0.98 s
Seismic Response Coefficient	C_{S_X} = 0.01 (ASCE 7-16 1.4-1) C_{S_Y} = 0.01 (ASCE 7-16 1.4-1)	C_{S_X} = 0.0135 (ASCE 7-16 12.8-3) C_{S_Y} = 0.0140 (ASCE 7-16 12.8-3)	C_{S_X} = 0.0169 (ASCE 7-16 12.8-3) C_{S_Y} = 0.0263 (ASCE 7-16 12.8-3)
Seismic Base Shear (ASCE 7-16, §12.8.1)	V_{BASE_X} = 647 kips (2878 kN) V_{BASE_Y} = 647 kips (2878 kN)	V_{BASE_X} = 623 kips (2771 kN) V_{BASE_Y} = 646 kips (2874 kN)	V_{BASE_X} = 530 kips (2358 kN) V_{BASE_Y} = 826 kips (3674 kN)

Table 3. Modes, Response Coefficients, and Seismic Base Shear values determined from IBC.

	CBC	IBC (Exosure B)	IBC (Exosure D)
Prototype 1	16" (406 mm) Core (Base to Lvl 10) 12" (305 mm) Core (Base to Lvl 10)	20" (508 mm) Core (Base to Lvl 6) 16" (406 mm) Core (Lvl 6 to Lvl 10) 12" (305 mm) Core (Lvl 10 to Roof)	26" (660 mm) Core (Base to Lvl 5) 24" (610 mm) Core (Lvl 5 to Lvl 10) 20" (508 mm) Core (Lvl 10 to Lvl 20) 16" (406 mm) Core (Lvl 20 to Roof)
		Web walls remain 10" (254 mm) for CBC and IBC models	
Prototype 2	10" (254 mm) Middle Web 12" (305 mm) Outer Webs & Flanges	10" (254 mm) Middle Web 12" (305 mm) Outer Webs 20" (508 mm) Flanges (Base to Lvl 3) 16" (406 mm) Flanges (Lvl 3 to Lvl 5) 12" (305 mm) Flanges (Lvl 5 to Roof)	10" (254 mm) Middle Web 12" (305 mm) Outer Webs 24" (610 mm) Flanges (Base to Lvl 3) 20" (508 mm) (Lvl 3 to Lvl 7) 12" (305 mm) Flanges (Lvl 7 to Roof)
Prototype 3	10" (254 mm) Core Walls	10" (254 mm) Core Walls	12" (305 mm) Core Walls

Table 4. Prototype Building core wall thickness.

in the figures, both story shears and overturning moments increase as a result of the updated provisions in IBC.

For Prototype Building 1, base shear and base overturning moment increases approximately 50 percent for exposure B and approximately 90 percent for exposure D, from CBC to IBC. For Prototype Building 2, base shear increases around 30 percent, and base overturning moment increases about 40 percent for exposure B and 80 and 90 percent, respectively, for exposure D, from CBC to IBC.

For Prototype Building 3, base shear increases about 50 percent in the Y-direction for seismic and exposure B wind, from CBC to IBC. For exposure D, the base shear increases about 120 percent in the Y-direction and 50 percent in the X-direction, from CBC to IBC. Base overturning moment increases about 85 percent in the Y-direction for seismic and 55 percent for exposure B wind, from CBC to IBC. For exposure D, the base overturning moment increases about 135 percent in the Y-direction and 62 percent in the X-direction, from CBC to IBC.

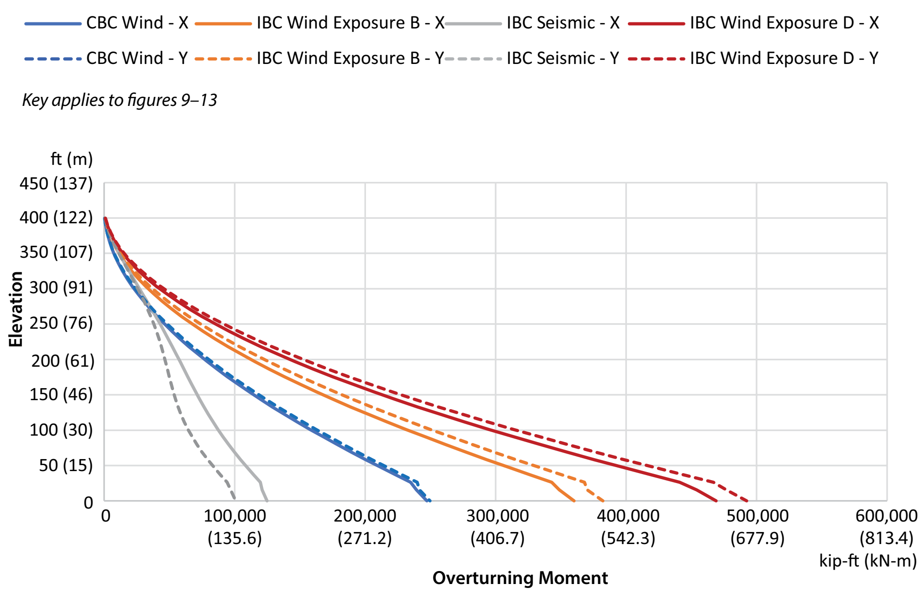


Figure 9. Overturning moment (strength level) for Prototype Building 1.

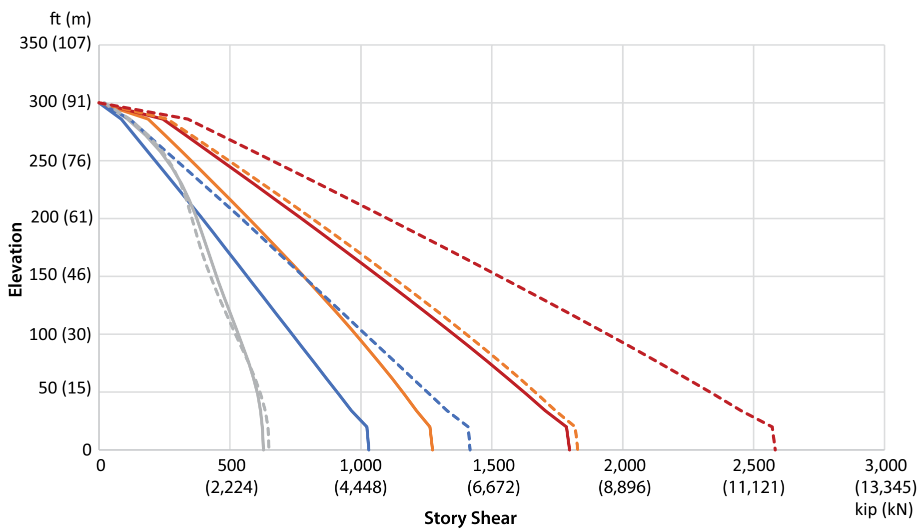


Figure 10. Story shear (strength level) for Prototype Building 2.

Foundation Design

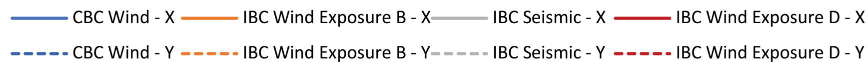
Belled caissons are utilized for the foundation type to support all three prototypes. The foundations are designed with a concrete compressive strength of 6,500 to 10,000 psi (44,816 to 68,948 kPa). For CBC design, the caisson diameter is controlled by two parameters: a maximum 3:1 ratio of the bell diameter to the caisson diameter and an upper-bound limit on the concrete compressive stress of 0.25 feet (76 millimeters). For IBC design, the caisson diameter is controlled by two parameters: a maximum 3:1 ratio of the bell diameter to the caisson diameter and an upper-bound limit on the concrete compressive stress of 0.30 feet (91 millimeters). Additionally, a minimum reinforcement ratio of 0.005 is used for caissons.

Cost Comparison

In order to understand the cost effects, two Chicago-based contractors provided unit costs for comparisons (see Table 5). Based on the calculated structural quantities, cost differentials were approximated for each prototype building (see Figure 14). Additionally, these cost differentials were also compared to total structural cost (represented as a percentage premium from CBC total structural cost (see Figure 15).

Conclusion

The adoption of the 2019 CBC will bring Chicago in line with widely adopted national standards. The lakefront of Chicago produces two wind exposure categories that are to be considered when prescriptive code provisions are used for design. Although wind and seismic loading demand on buildings may increase, the sampling study considered indicates that the increase in structural cost will generally not be significant except when construction is closer to 400 feet (122 meters) high, with lakefront exposure. Project teams should consider impact of structural premiums on projects, and further consider employing wind tunnel testing for buildings in the 300-to-400-foot (90-to-122-meter) range, when this testing can provide a significant cost benefit. ■



Key applies to figures 9–13

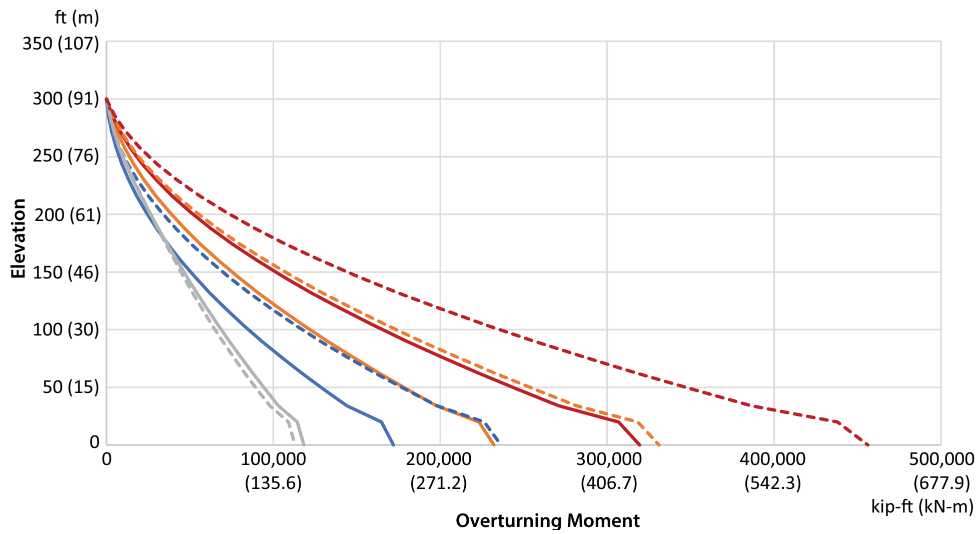


Figure 11. Overturning moment (strength level) for Prototype Building 2.

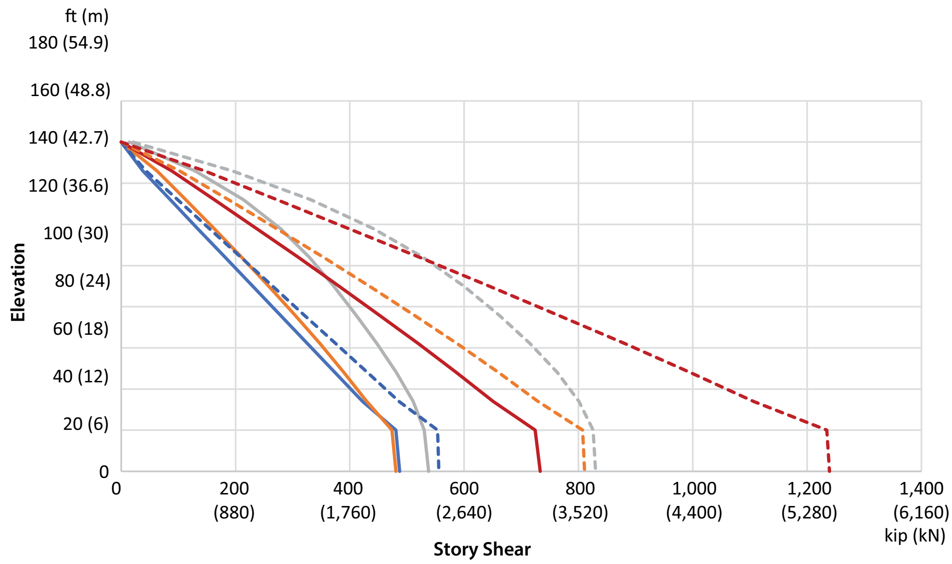


Figure 12. Story shear (strength level) for Prototype Building 3.

Structural/Material Component		Estimated Unit Cost
Superstructure	Concrete	\$360/cu yd (\$275/m³)
	Reinforcing steel placement	\$2,500/ton (\$2,268/metric ton)
Caisson Foundation	Shaft. Excavation	\$5/cu ft (\$0.15/m³)
	Bell Excavation	\$15/cu ft (\$0.45/m³)
	Caisson Concrete	\$175.00/cu yd (\$134/m³)
	Caisson Reinforcing Steel	\$2,500/ton (\$2,268/metric ton)

Table 5. Estimated material unit rate costs.

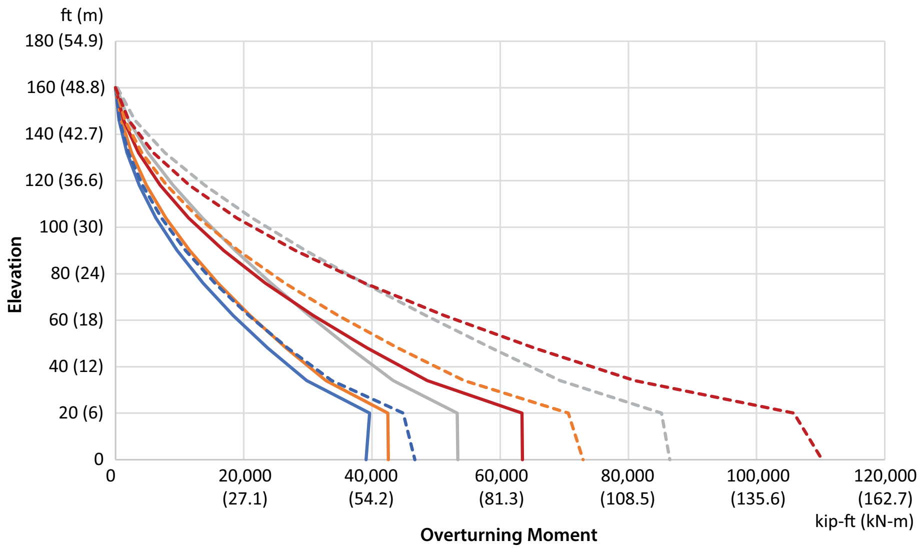


Figure 13. Overturning moment (strength level) for Prototype Building 3.

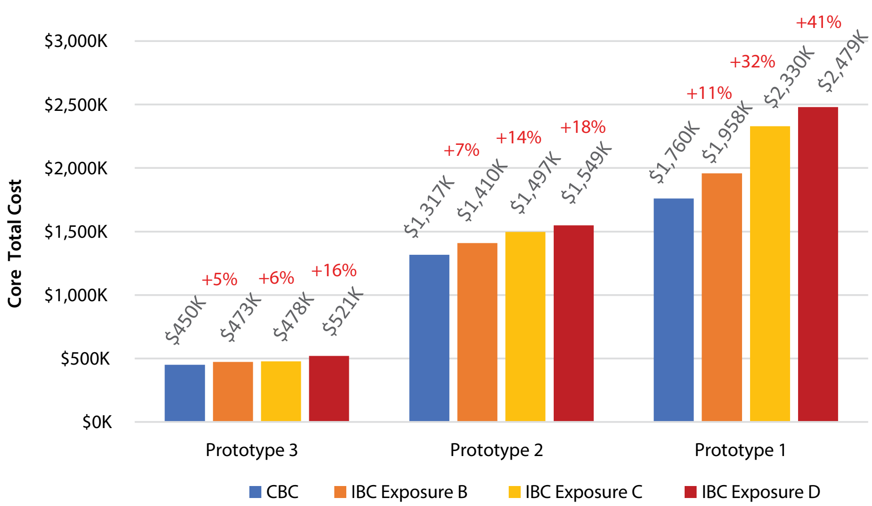


Figure 14. Total (core) costs for each prototype building based on IBC and CBC combined (IBC Exposure categories B, C and D).

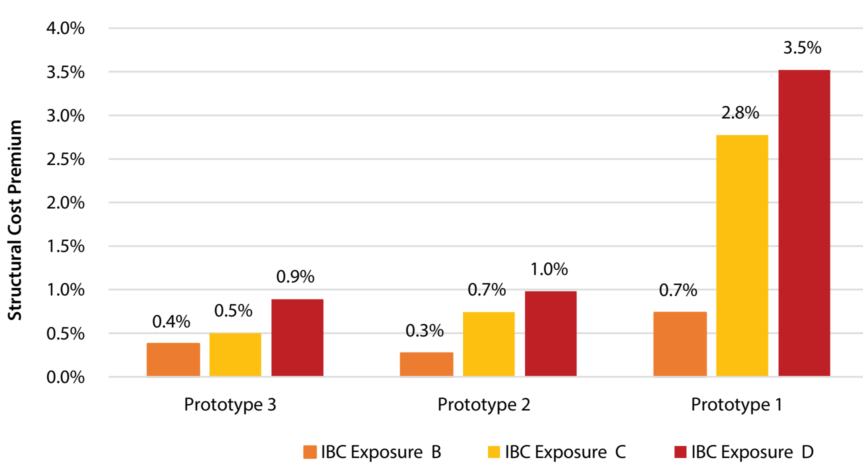


Figure 15. Structural cost premiums for each prototype building based on IBC vs. CBC.

Unless otherwise noted, all image credits in this paper are to the authors.

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Editor's Note: A full version of this paper is available online at store.ctbuh.org. This is the first in a series of white papers that CTBUH will publish in relation to code changes affecting tall building design.

Codes

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