Chicago Building Code Modernization

Comparison of Prototype Building Designs

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Council on Tall Buildings and Urban Habitat

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1.0 Introduction

1.1 Background

For many years local design and construction industries understood there was a need to better align the Chicago 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) Chicago Building Code or the new 2019 Chicago Building Code which references 2018 International Building Code (referred to as "IBC" in this document). After 1 August 2020, all new designs submitted for approval will need to conform to the new 2019 Chicago Building Code (IBC).

1.2 Objective and Scope

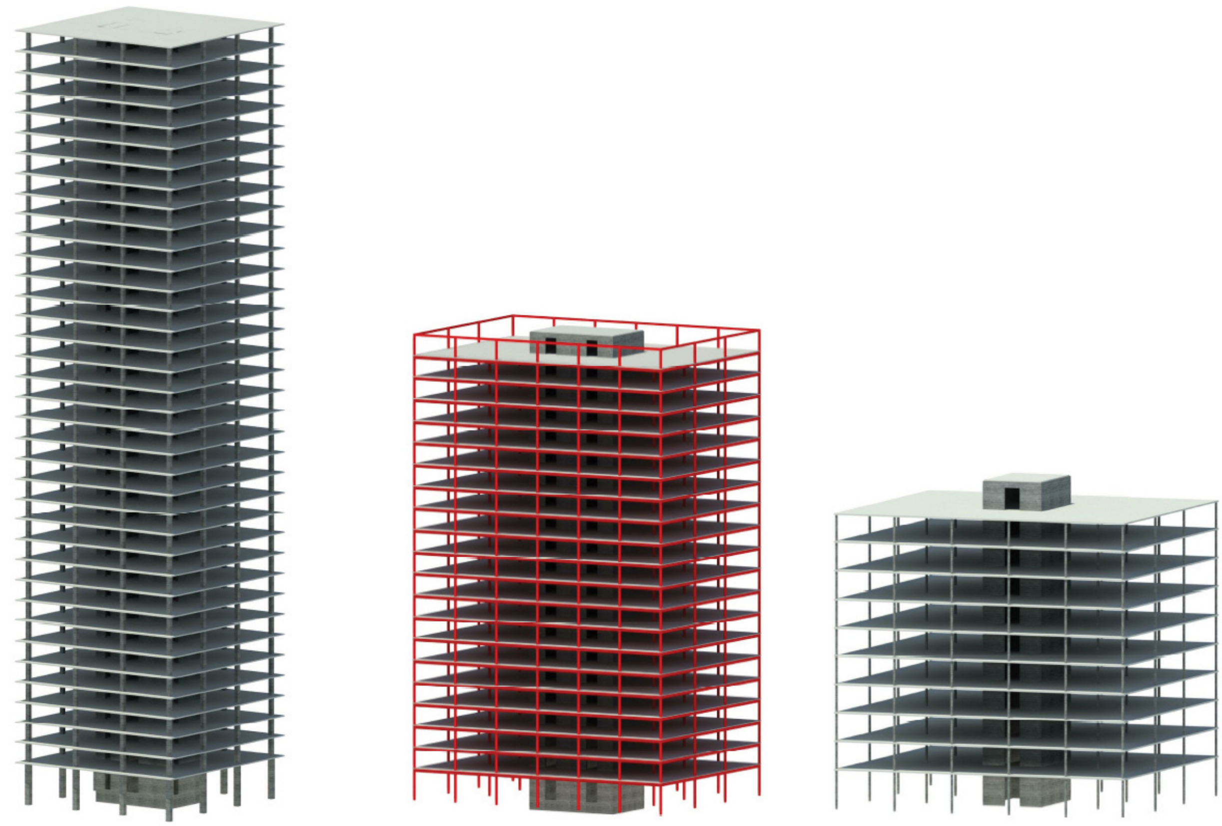
Structural engineers familiar with the CBC and IBC recognize that design lateral forces developed by the two codes can vary significantly. Low-rise buildings may realize a reduction in wind loads with the IBC, but as a building gets taller and the exposure category increases (as specified by ASCE 7 Exposure 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 prototype building is provided in following section.



Prototype 1

37-story Residential Tower
400 feet (121.9 meters) tall
100 x 100 feet
(30.5 x 30.5 meters)

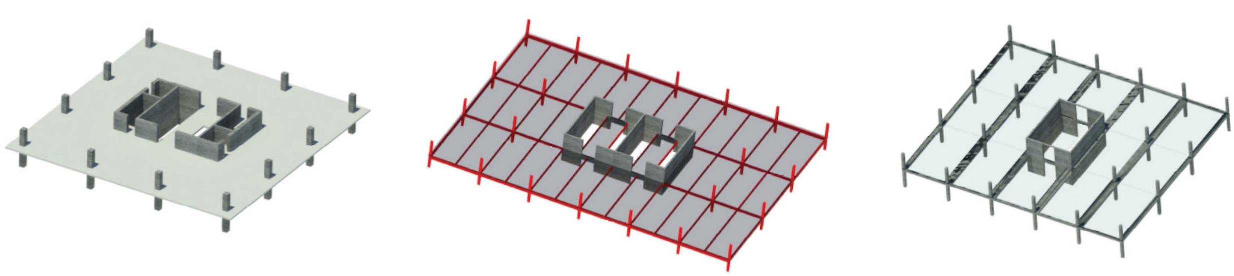
Prototype 2

20-story Office Building
286 feet (87.2 meters) tall
180 x 130 feet
(54.9 x 39.6 meters)

Prototype 3

10-story Office Building
160 feet (48.8 meters) tall
150 x 130 feet
(45.7 x 39.6 meters)

Figure 1. Isometric view of the prototype buildings.



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Prototype 3

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150 x 130 feet
(45.7 x 39.6 meters)

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

2.0 Prototype Building Description

2.1 Prototype Building 1

Prototype Building 1 is a residential tower with a ground floor lobby with a 15-foot, 8-inch (4.8-meter) ceiling, 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 399 feet, 8 inches (121.8 meters) (see Figure 2), just below the 400-foot (122-meter) threshold requirement for wind tunnel testing per IBC, with columns around the perimeter spaced at 30 feet on center (see Figure 3). 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).

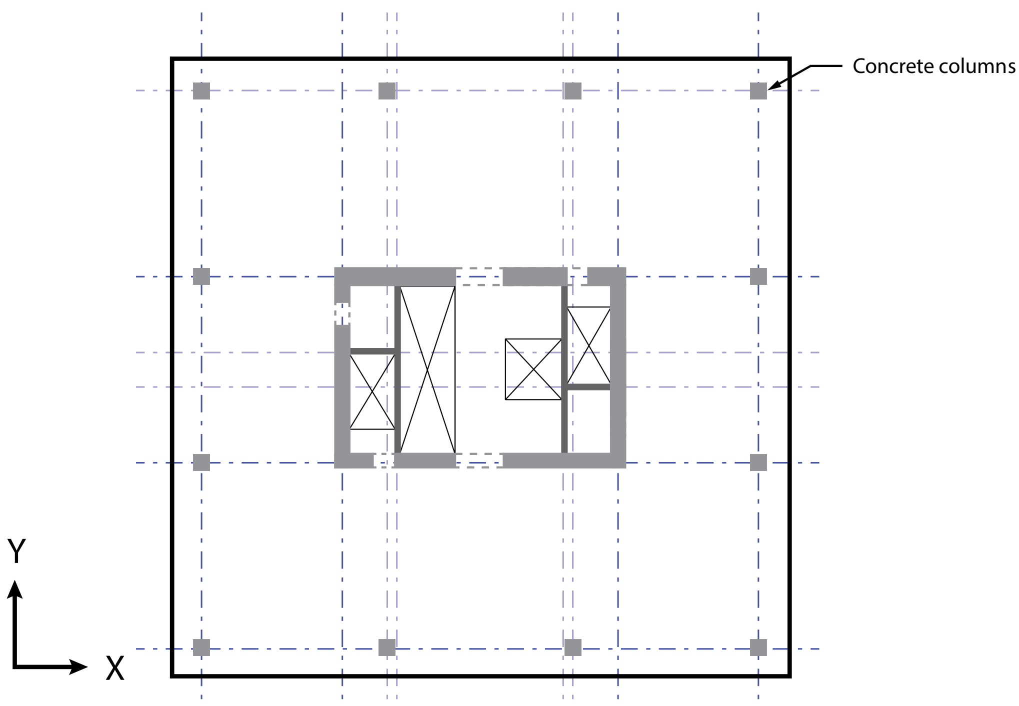


Figure 3. Typical floor plan of Prototype Building 1.

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.

2.2 Prototype Building 2

Prototype Building 2 is an office building with a ground floor lobby with a 20-foot (6.1-meter) ceiling, 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). An exterior

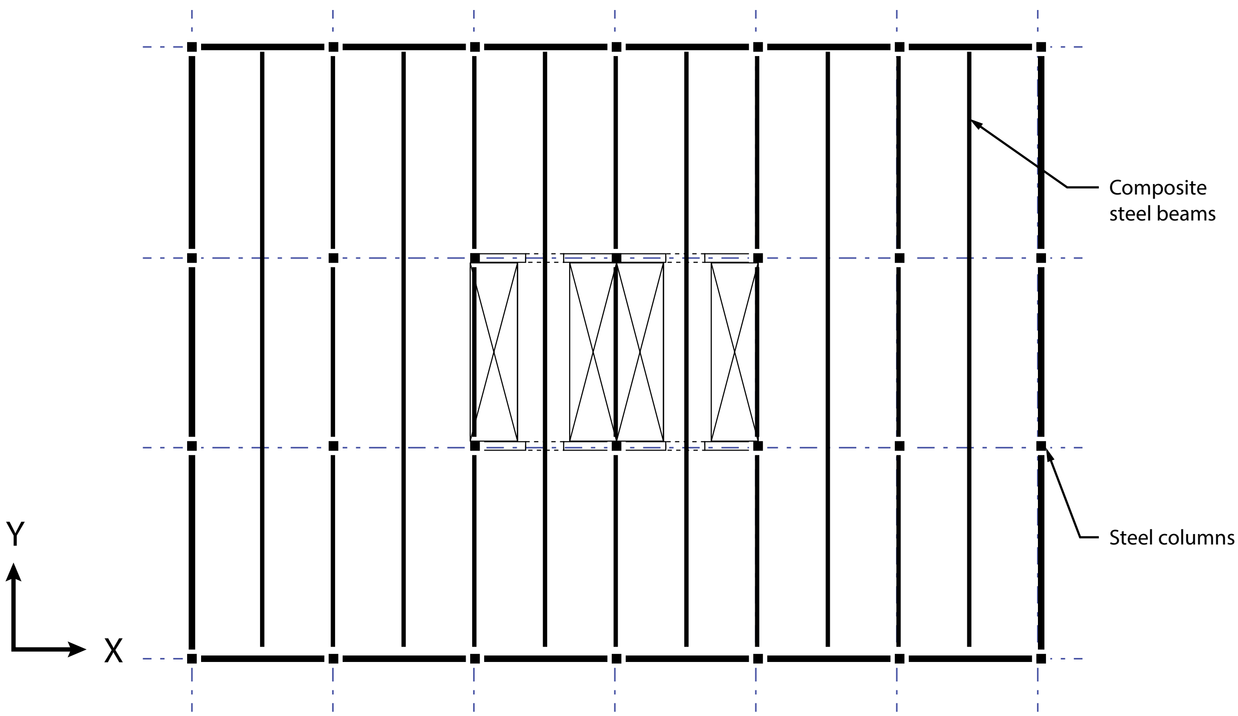


Figure 4. Typical floor plan of Prototype Building 2.

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 (see Figure 2) is 180 feet by 130 feet (54.9 meters by 39.6 meters) 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 4). The floor system consists of 3-1/4-inch (83-millimeter) lightweight concrete on a 3-inch (76-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).

2.3 Prototype Building 3

Prototype Building 3 is an office building with a ground floor lobby 20-foot- (6.1-meter)-high ceiling, 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). 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 (see Figure 2) 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 5). 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).

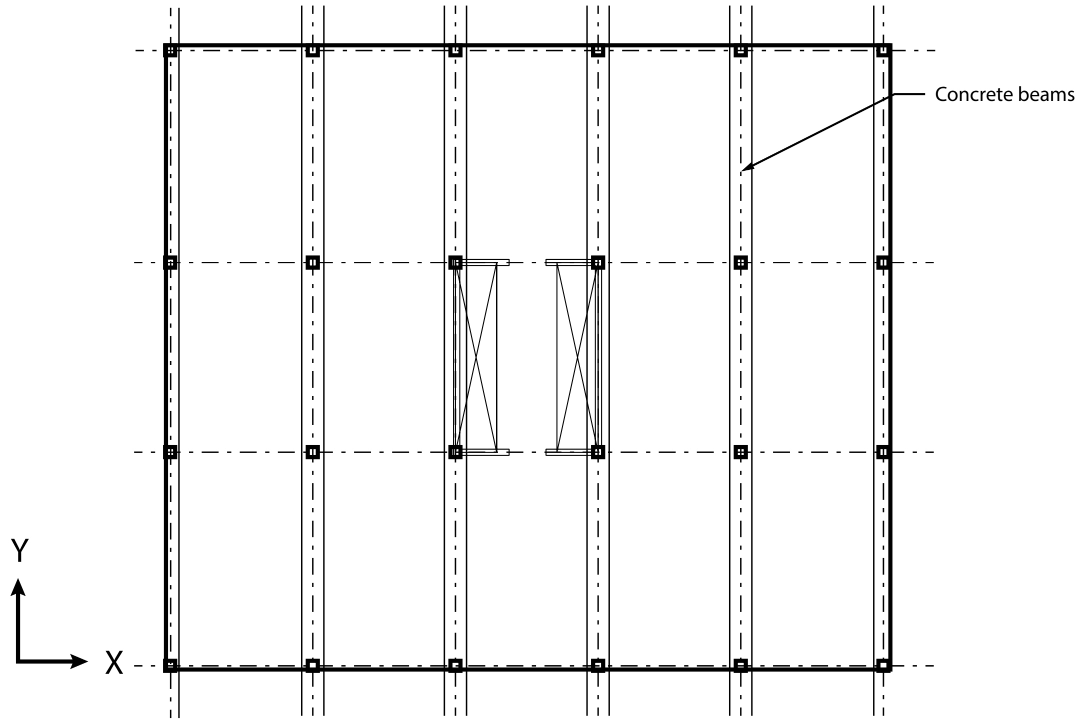


Figure 5. Typical floor plan of Prototype Building 3.

3.0 Comparison of Building Codes

3.1 Pre-2019 Chicago Building Code (CBC)

The pre-2019 Chicago Building Code requirements for construction of new buildings are primarily found in Title 13 and Title 15 of the Chicago Municipal Code. This code was adopted in 1949, and has been modified several times over the years. The structural standards referenced in the CBC have not been updated since the 1980s.

The CBC references the following codes and standards:

- ANSI A58.1, Minimum Design Loads for Buildings and Other Structures,1982, American National Standard.
- ACI 318, Building Code Requirements for Structural Concrete, 1983, American Concrete Institute.
- AISC 1989 ASD or AISC 1986 LRFD, American Institute of Steel Construction, Inc.

3.2 2019 Chicago Building Code (IBC)

The new 2019 Chicago Building Code is identical to the 2018 International Building Code, except as modified by specific provisions of Title 14B.

The IBC references the following US codes and standards:

- ASCE 7, Minimum Design Loads for Buildings and Other Structures, 2016, American Society of Civil Engineers.
- ACI 318, Building Code Requirements for Structural Concrete, 2014, American Concrete Institute.
- AISC 360, Specification for Structural Steel Buildings, 2016, American Institute of Steel Construction, Inc.

4.0 Design Analysis and Criteria

4.1 Material Properties

The following tables summarize the material properties used in the design and analysis of the prototype buildings. The material properties are held constant across all analyses in order to produce consistent and comparable results between the CBC and IBC analyses/designs. The material properties shown below apply to all three prototype buildings unless noted otherwise.

- Normal weight concrete (NWC) is assumed to have a unit weight of 150 pounds per cubic foot (pcf) (2,403 kilograms per cubic meter (kg/m^3)). Lightweight concrete (LWC) is assumed to have a unit weight of 115 pcf (1,842 kg/m^3). Minimum Characteristic Cylinder Compression Strength, f'c (at 28 days typically) shall be as follows in Table 1:

Structural Element	Concrete Density	Concrete Strength
Shear Walls + Link Beams – Building 1	NWC	10,000 psi (68,948 kPa)
Beams	NWC	8,000 psi (55,158 kPa)
Caissons	NWC	6,500 psi (44,816 kPa) to 10,000 psi (68,948 kPa)

- Concrete Reinforcement:

Reinforcement Type	ASTM Standard and Grade
Deformed Bars	ASTM A615 Grade 60

Table 1. Concrete density, strength, and reinforcement types as specified in the new CBC code and applied to all three prototype buildings in this study.

4.2 Applied Loads

4.2.1 Wind Loads

CBC Wind Loads

Sections 13-52-300 and 13-52-310 of the CBC provide the following provisions for wind loads:

- The CBC prescriptive code height limit of 600 feet (183 meters) applies.
- Wind loads are based on a basic wind speed of 75 miles per hour (33.5 m/s) defined as the annual extreme fastest-mile speed, 10 meters above ground.
- The horizontal design wind pressures are provided in Table 13-52-310 and are shown in Table 2. These wind speeds are based on a 50-year recurrence interval.
- Wind pressure applications are provided to allow for wind in any direction. This was addressed in the load combinations by applying wind in each principal direction, and then applying wind at a 45-degree angle.

Height	Column (A) Main Force-Resisting System Wind Pressure	Column (B) Wind Pressure: Components/Cladding (Other than Corner)	Column (B) Wind Pressure: Components/Cladding (Corner)
≤200 ft ≤61 m	20 psf 0.96 kPa	25 psf 1.20 kPa	30 psf 1.44 kPa
300 ft 91.44 m	21 psf 1.01 kPa	27 psf 1.29 kPa	32 psf 1.53 kPa
400 ft 121.92 m	25 psf 1.20 kPa	32 psf 1.53 kPa	38 psf 1.82 kPa
500 ft 152.40 m	28 psf 1.34 kPa	35 psf 1.68 kPa	41 psf 1.96 kPa
600 ft 182.88 m	31 psf 1.48 kPa	39 psf 1.87 kPa	45 psf 2.15 kPa
700 ft 213.36 m	33 psf 1.58 kPa	42 psf 2.01 kPa	49 psf 2.35 kPa
800 ft 243.84 m	36 psf 1.72 kPa	45 psf 2.15 kPa	54 psf 2.59 kPa
900 ft 274.32 m	39 psf 1.87 kPa	49 psf 2.35 kPa	58 psf 2.78 kPa
1000 ft 304.80 m	42 psf 2.01 kPa	53 psf 2.54 kPa	63 psf 3.02 kPa

Table 2. Minimum Wind Pressures Per CBC (Table 13-52-310)

IBC Wind Loads
Code-prescribed parameters used in calculating the wind loads applicable to the Main Wind Force-Resisting System (MWFRS) are shown in Table 3.

Parameter	Value	Code reference
Risk Category	II	IBC, Table 1604.5
Wind Importance Factor, Iw	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 (39.4 m/s)	
(39.3 m/s)	ASCE 7-16, Figure CC.2-3	
Building Enclosure	Enclosed	
Internal Pressure Coefficient GCpi	+/- 0.18	ASCE 7-16, Table 26.13-1

Table 3. Wind design parameters for the three prototype structures.

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, Fig. 27.4-8. Base Chicago wind exposures are shown in Figure 6.

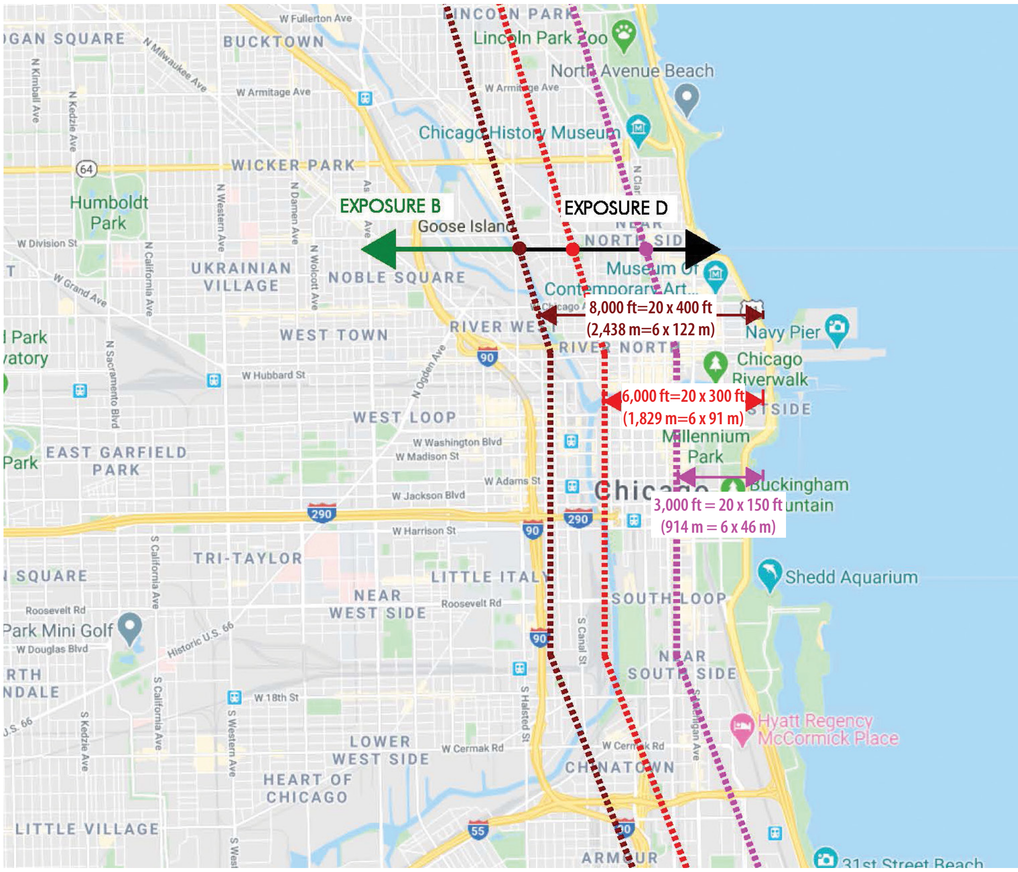


Figure 6. Chicago wind exposure categories and locations.

Figures 7 through 12 provide comparisons of the CBC wind to the IBC wind for exposures B, C (provided for reference) and D for prototype buildings 1, 2 and 3. Note that for the strength graph below, the CBC wind pressures include a factor of 1.3 (directionality effects included) to make them comparable to IBC ultimate wind pressures. For the service graph below, the IBC wind pressures are based on the 50-year MRI Wind Speed for Drift.

CBC
IBC (Exposure B)
IBC (Exposure C)
IBC (Exposure D)

Key applies to figures 7–12.

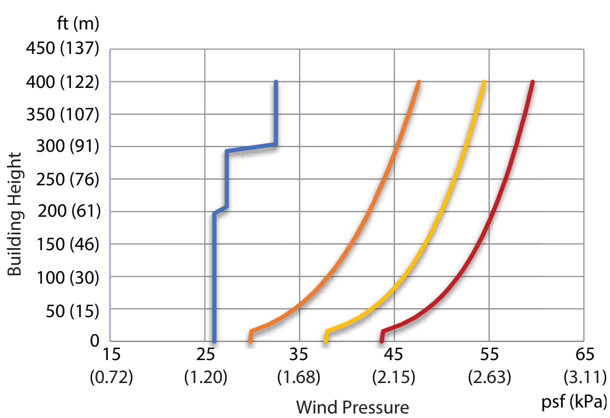


Figure 7. Strength design wind pressures for Prototype Building 1.

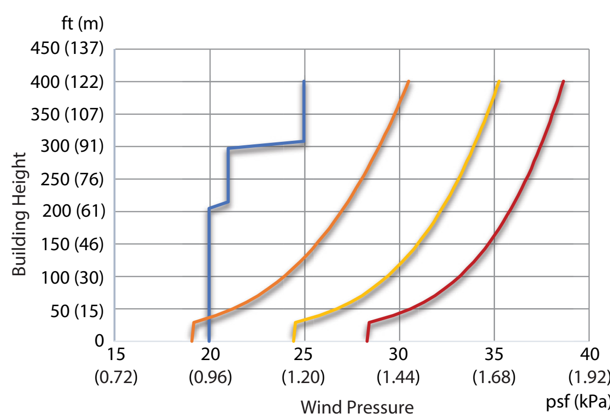


Figure 8. Service design wind pressures for Prototype Building 1.

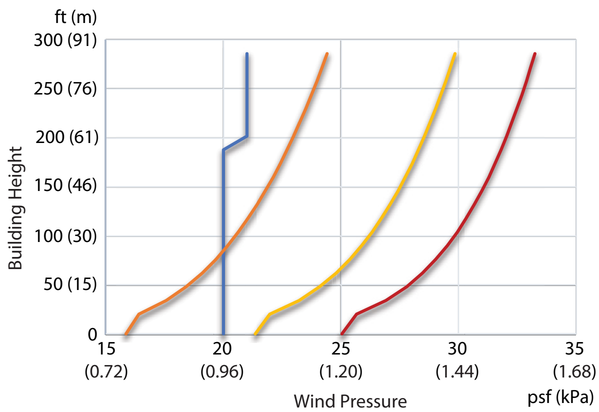


Figure 9. Strength design wind pressures for Prototype Building 2.

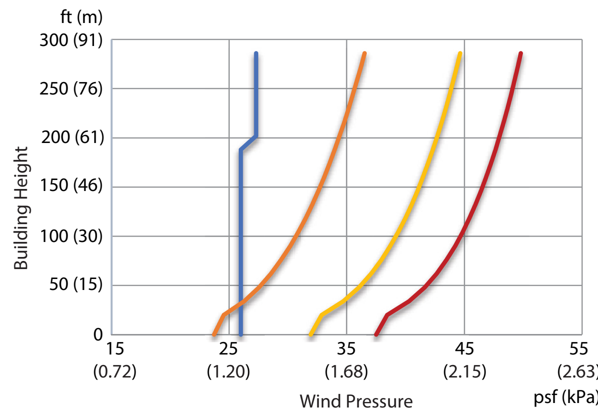


Figure 10. Service design wind pressures for Prototype Building 2.

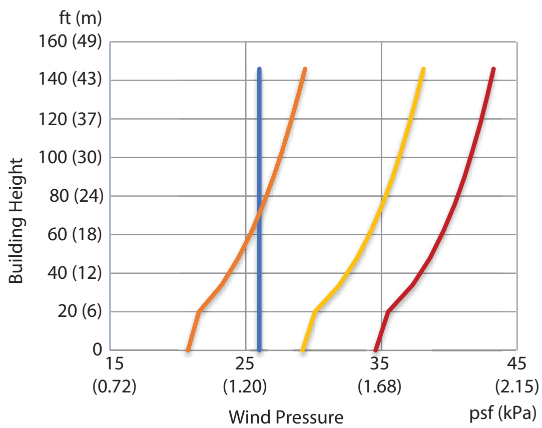


Figure 11. Strength design wind pressures for Prototype Building 3.

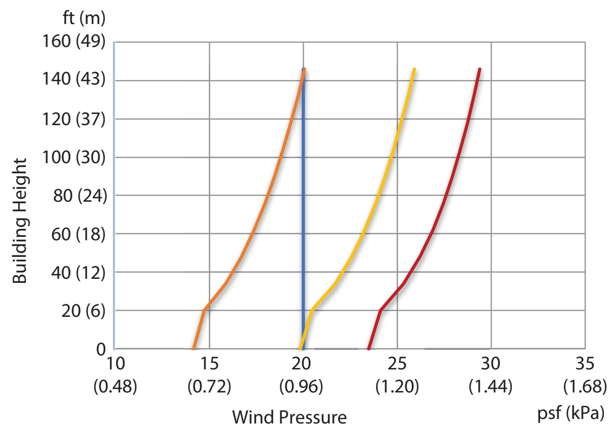


Figure 12. Service design wind pressures for Prototype Building 3.

Although the Wind Exposure D creates higher loading, the Chicago Wind Climate model (see Figure 13) suggests that wind loading from the easterly winds is expected to be significantly lower than prevailing strong winds from south and west.

4.2.2 Seismic Loads

CBC Seismic Loads

Per Title 13, Section 13-52-340 of CBC states,

"Special provisions for seismic design shall not apply. The basic wind design provisions for buildings, portions thereof, cladding and components and other structures shall apply."

Therefore, seismic loads are not considered in the CBC analysis and design of the Prototype Buildings.

IBC Seismic Loads

IBC Section 1613.1, which was incorporated into the 2019 CBC by reference, states:

"Every structure, and portion thereof, including nonstructural components that are permanently attached to structures and their supports and attachments, shall be designed and constructed to resist the effects of earthquake motions in accordance with Chapters 11, 12, 13, 15, 17 and 18 of ASCE 7, as applicable."

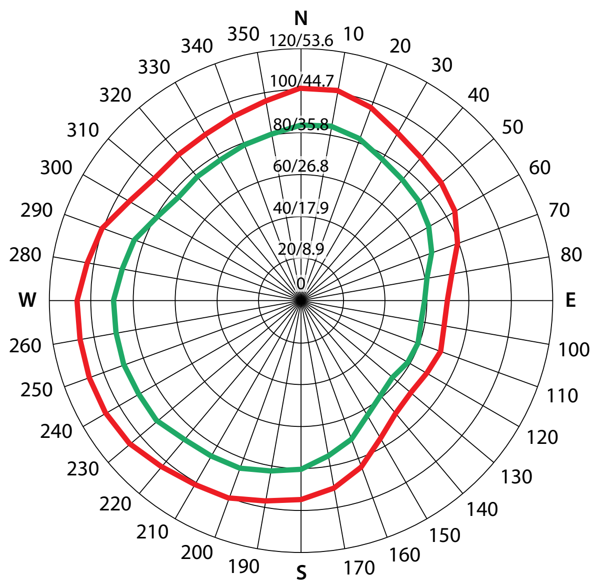


Figure 13. Wind rose for the Chicago area, applied to all three prototype buildings.

Therefore, seismic loads are considered in the IBC analysis and design of the prototype buildings. The site coefficients and adjusted maximum considered earthquake spectral response acceleration parameters used for this analysis are provided in Table 1613.2.3 of IBC and shown in Table 4. Site Class D is used for the analysis of the prototype buildings per Section 1613.2.2 of IBC.

ASCE 7-16 defines the acceptable analytical procedures for structures designed for earthquake loads based on their structural characteristics and Seismic Design Category. Table 12.6-1 of ASCE 7-16 permits a Modal Response Spectrum Analysis for all structures with a Seismic Design Category of B.

Site Class	Maximum Spectral Response Accelerations		Design Spectral Response Accelerations		Seismic Design Category Risk Category	
	S_{MS}	S_{M1}	S_{DS}	S_{D1}	I, II, or III	IV
A	0.100	0.053	0.067	0.035	A	A
B	0.113	0. 53	0.075	0.035	A	A
C	0.163	0.099	0.108	0.066	A	A
D	0.200	0.155	0.133	0.103	B[a]	C
E	0.300	0.277	0.200	0.185	C	D
F	Note b	Note b	Note b	Note b	Note c	

Notes:

a. The *structure* shall be assigned to *Seismic Design Category* A where the *mean roof height* does not exceed 60 feet (18.3 m) and the horizontal distance between vertical elements of the *seismic force-resisting system* does not exceed 40 feet (12.2 m).

b. Values shall be determined in accordance with Section 11.4.8 of ASCE 7.

c. Determine in accordance with ASCE 7.

Table 4. Site coefficients and adjusted maximum considered earthquake spectral response acceleration parameters.

The following parameters in Table 5 are utilized based on the code-prescribed requirements and a representative Chicago West Loop geotechnical profile. See Section 6.0 for further foundation discussion.

Parameter	Value	Code reference
Risk Category	II	IBC, Table 1604.5
Seismic Importance Factor, Ie	1.00	ASCE 7-16, Table 1.5-2
Seismic Design Category	B	IBC, Table 1613.2.3
SDS	0.133g	IBC, Table 1613.2.3
SD1	0.103g	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, CS		See Table 19.
Response Modification Factor, R	4	ASCE 7-16, Table 12.2-1
Deflection Amplification Factor, Cd	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 5. Seismic design parameters for the three prototype structures.

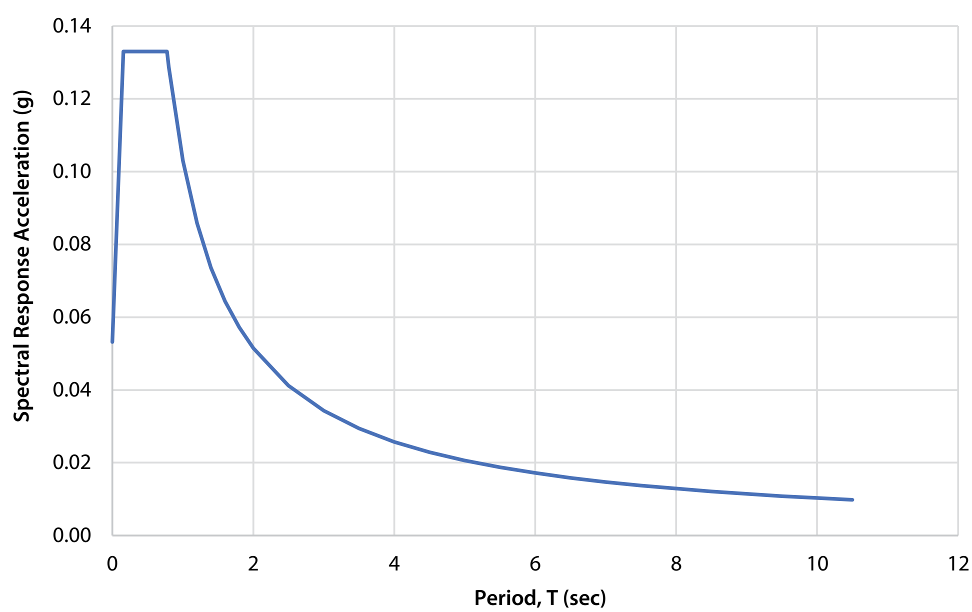


Figure 14. Design response spectrum curve for Site Class D developed for prototype buildings per ASCE 7-16.

The response spectrum is scaled in the ETABS structural model to 100 percent of the calculated base shear per 12.9.1.4 per ASCE 7-16 (see Figure 14). The modal parameters and coefficients used to calculate the base shear are provided in Table 6.

	Prototype 1 40 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 (2,878 kN) V_{BASE_Y} = 647 kips (2,878 kN)	V_{BASE_X} = 623 kips (2,771 kN) V_{BASE_Y} = 646 kips (2,874 kN)	V_{BASE_X} = 530 kips (2,358 kN) V_{BASE_Y} = 826 kips (3,674 kN)

Table 6. Modes, response coefficients, and seismic base shear values determined from IBC.

4.2.3 Gravity Loads

Dead loads are defined as the weight of all permanent structural and non-structural components of the building, including, but not limited to, floor finishes, raised flooring systems, walls, ceilings, roofing, stairs, walkways, fixed mechanical, electrical, and plumbing equipment, and any overburden. The exterior curtain wall is assumed to weigh 15 psf (0.7 kPa) over the vertical tower surface and is applied at the perimeter of the building.

Live loads are defined to be loads due to the intended use and occupancy of a floor area, and include all moveable equipment. Live loads are listed in the table to the right. Required minimum live loads for the usages of the prototype buildings are the same for both the CBC and IBC.

Location	Unfactored Superimposed Dead Load (psf/kPa)	Unfactored Live Load (psf/kPa)
Residential Floors	25 (1.2)	40 (1.9)
Mechanical Floors	60 (2.9)	125 (6.0)
Office Floors	15 (0.7)	50* (2.4)

*Additional partition loads are 20 psf (1.0 kPa) for CBC and 15 psf (0.7 kPa) for IBC.

Table 7. Applied dead and live loads.

Reduction in live load is allowed per ASCE 7. Live loads are not reduced for the following: roof, storage, mechanical, and live loads greater than 100 psf (4.8 kPa). Per CBC Section 13-52-210, for a tributary area greater than 900 square feet (83.6 square meters), live load can be reduced up to 50 percent. Per IBC Section 1607.11.1, live loads can be reduced up to 60 percent for members supporting more than one floor.

Gravity loads (other than structure self-weight) are seen in Table 7.

4.3 Load Combinations

The following basic load combinations were used in the analysis of the prototype buildings. Each structural model was evaluated with CBC load combinations as well as IBC load combinations. Section 13-52-340 of Title 13 (CBC) states seismic design shall not apply, but that the basic wind design provisions for buildings cladding and components shall apply. The IBC load combinations require that seismic loads be assessed in accordance with the procedure outlined in ASCE 7-16.

CBC Load Combinations
Section 13-52 of the Title 13 states that loads and load combinations are per ANSI A58.1, Section 2.

IBC Load Combinations
Section 1605 of IBC includes the load cases that are used in strength and serviceability checks.

4.4 ETABS FEA Model Combinations

The 3D finite-element modeling software ETABS was used to perform the finite element analysis (FEA) portion of this research. The shear walls (core), link beams, slabs and columns are included in the model. A rigid diaphragm is used for all floor levels.

The following general loading assumptions are used:

- Gravity loads are assigned as uniform shell loads. Live load reduction was considered for all gravity loading in accordance with IBC.
- The mass source is assigned by element mass and loading patterns. The overall mass source is equivalent to:
  - Wind Mass = SW+CLAD+0.50 SDL+0.25 LL+0.25 NRL
  - Seismic Mass = SW+CLAD+SDL+0.25 NRL

The following modeling assumptions are used:

- Pin supports are used for walls and columns at the ground level.
- Floor slabs are modeled with true thickness with their stiffness modified to reduce frame action (I_{eff} =0.25I_g).
- Rigid diaphragms are assigned to joints at each level.
- For Prototype Building 2, the deck and fill floors are modeled as a deck section membrane using the geometric properties.
- Shear walls are modeled as shell elements, uncracked and having full stiffness.
- Link beams are modeled as frame elements and are assumed to be cracked, with stiffness modifiers (I_{eff} =0.50I_g).
- Columns are modeled as frame elements and are assumed to be uncracked. The columns are not integral to the lateral/dynamic response of the building, but were included in the model for mass distribution.
- Mass based P-Delta analysis is considered for drift determination and element designs.

5.0 Core Design Comparison

The CBC modernization most significantly affects the lateral systems (concrete core shear walls) of the prototype buildings due to the increase in lateral wind forces. The following sections summarize the results of the lateral system design for the prototype buildings.

5.1 Prototype Shear Wall Design Thicknesses

Walls are sized to achieve code compliance and maintain reasonable levels of reinforcement. Table 8 summarizes the core wall thicknesses.

	CBC	IBC (Exp. B)	IBC (Exp. 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" 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) Flanges (Lvl 3 to Lvl 7) 12" (305 mm) Flanges (Lvl 7 to Roof)
Prototype 3	10" Core Walls	10" Core Walls	12" Core Walls

Table 8. Prototype Building core wall thickness.

5.2 Lateral Drift

Figures 15 and 16 illustrate the building drift for each prototype building under both CBC and IBC, exposure B and exposure D, respectively. Overall lateral displacements for 50-year return period wind loads are all less than the conventional limit of H/500, where H is defined as the total building height. As previously discussed, second-order (P-Delta) effects are considered in the behavior of the structural system of the buildings. Comparing CBC to IBC Exposure B, prototype buildings 1, 2 and 3 see an increase in maximum drift of 18, 27 and 6 percent, respectively.

Prototype 1 - CBC Drift - Max
Prototype 1 - IBC Drift - Max
Prototype 2 - CBC Drift - Max
Prototype 2 - IBC Drift - Max
Prototype 3 - CBC Drift - Max
Prototype 3 - IBC Drift - Max
H/500

Key applies to figures 15–16.

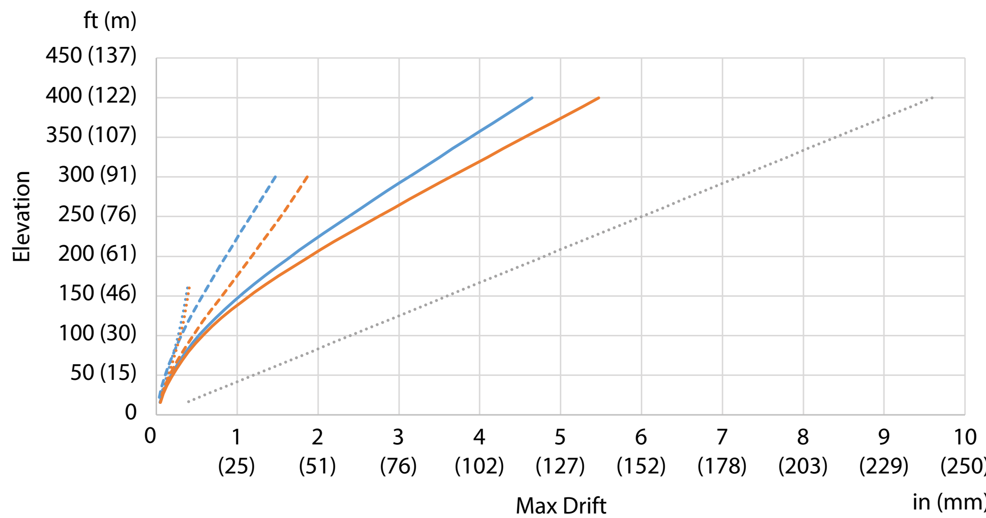


Figure 15. Exposure B maximum 50-year wind drifts for each prototype building.

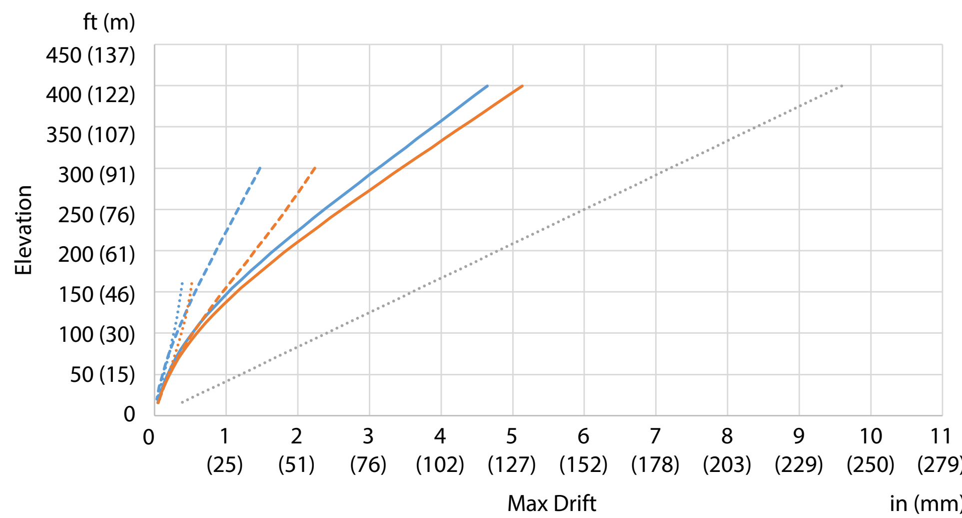


Figure 16. Exposure D maximum 50-year wind drifts for each prototype building.

For Exposure D, Prototype Buildings 1, 2 and 3 see an increase in max drift of 10, 52 and 34 percent, respectively. The increase in shear wall thickness for exposure D wind pressures limits the increase in overall displacement.

5.3 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 17, 19, and 21 show the story shear (strength level) for each prototype building. Figures 18, 20, and 22 show the overturning moment (strength level) for each prototype building. As shown 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 increase approximately 50 percent for exposure B and approximately 90 percent for exposure D, from CBC to IBC.

Key applies to figures 17–18.

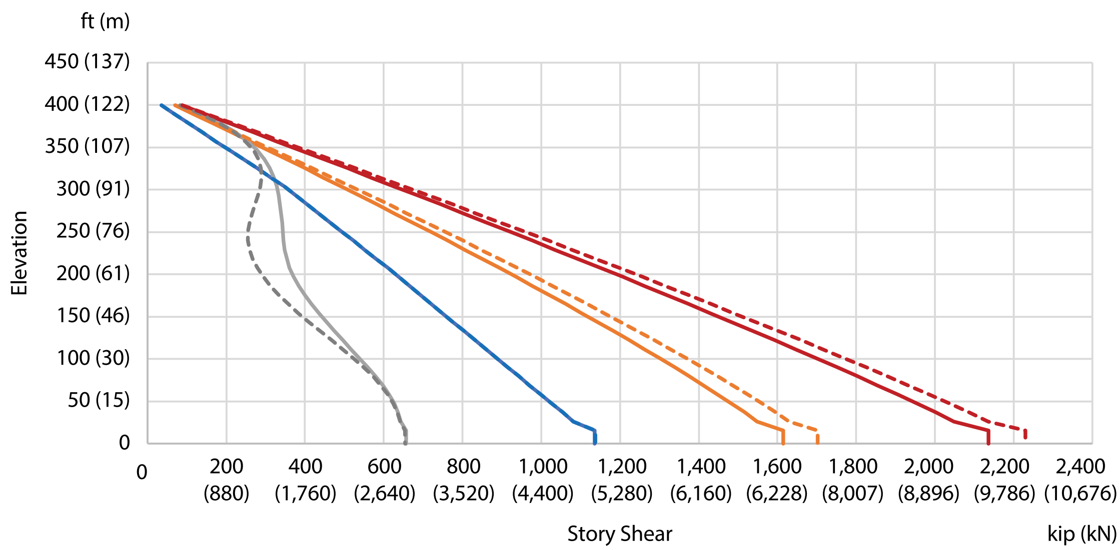


Figure 17. Story shear (strength level) for Prototype Building 1.

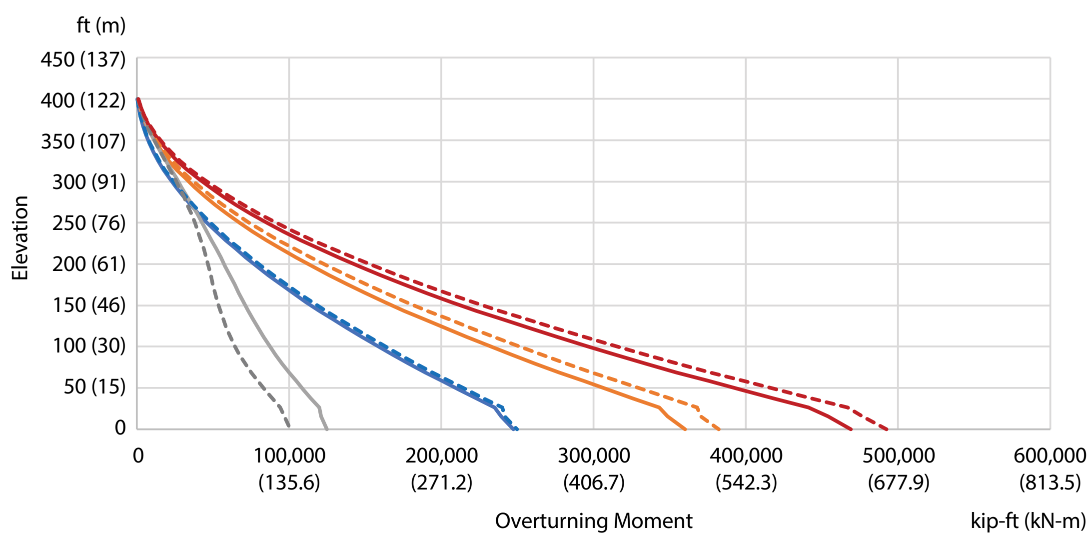


Figure 18. Overturning moment (strength level) for Prototype Building 1.

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

CBC Wind - X
CBC Wind - Y
IBC Wind Exp. B - X
IBC Wind Exp. B - Y
IBC Seismic - X
IBC Seismic - Y
IBC Wind Exp. D - X
IBC Wind Exp. D - Y

Key applies to figures 19–20.

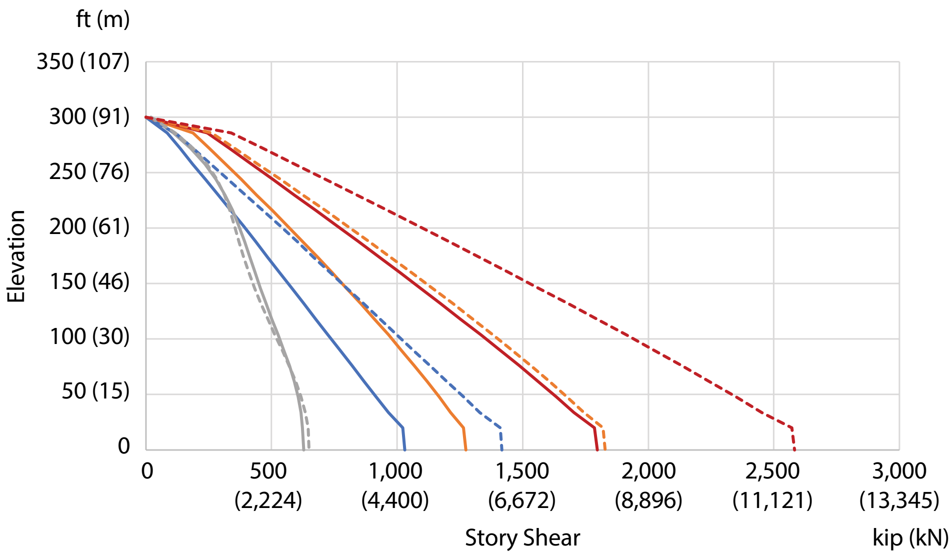


Figure 19. Story shear (strength level) for Prototype Building 2.

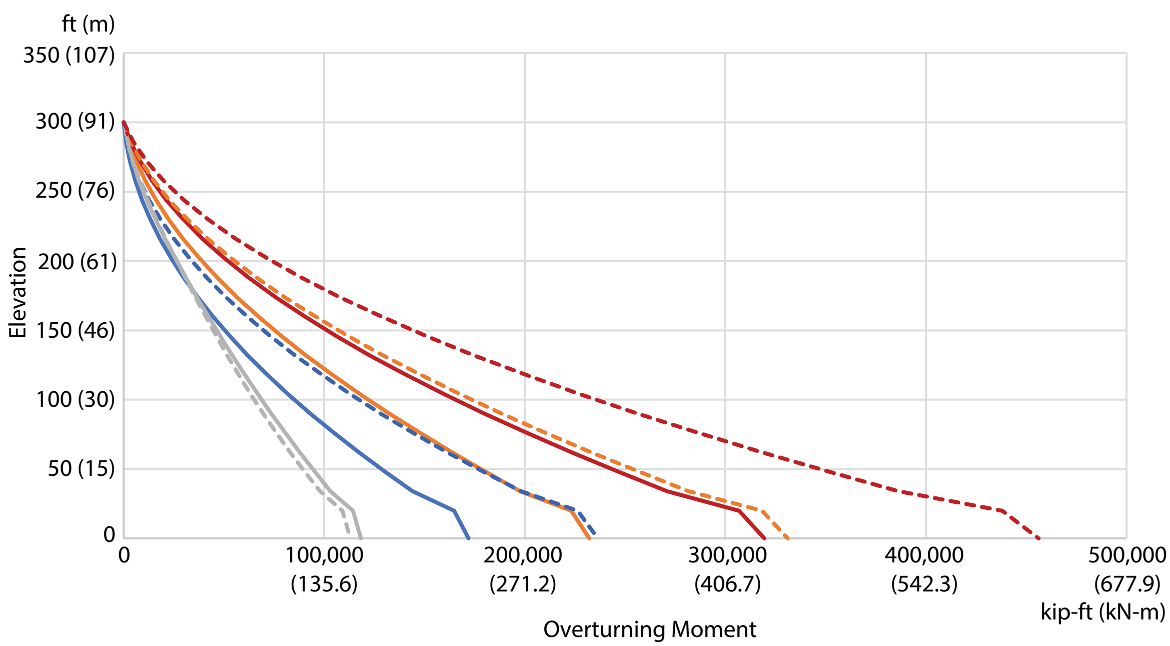


Figure 20. Overturning moment (strength level) for Prototype Building 2.

For Prototype Building 3, base shear increases approximately 50 percent in the Y-direction for seismic and exposure B wind, from CBC to IBC. For exposure D, the base shear increases approximately 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 around 135 percent in the Y-direction and 62 percent in the X-direction, from CBC to IBC.

CBC Wind - X
CBC Wind - Y
IBC Wind Exp. B - X
IBC Wind Exp. B - Y
IBC Seismic - X
IBC Seismic - Y
IBC Wind Exp. D - X
IBC Wind Exp. D - Y

Key applies to figures 21–22.

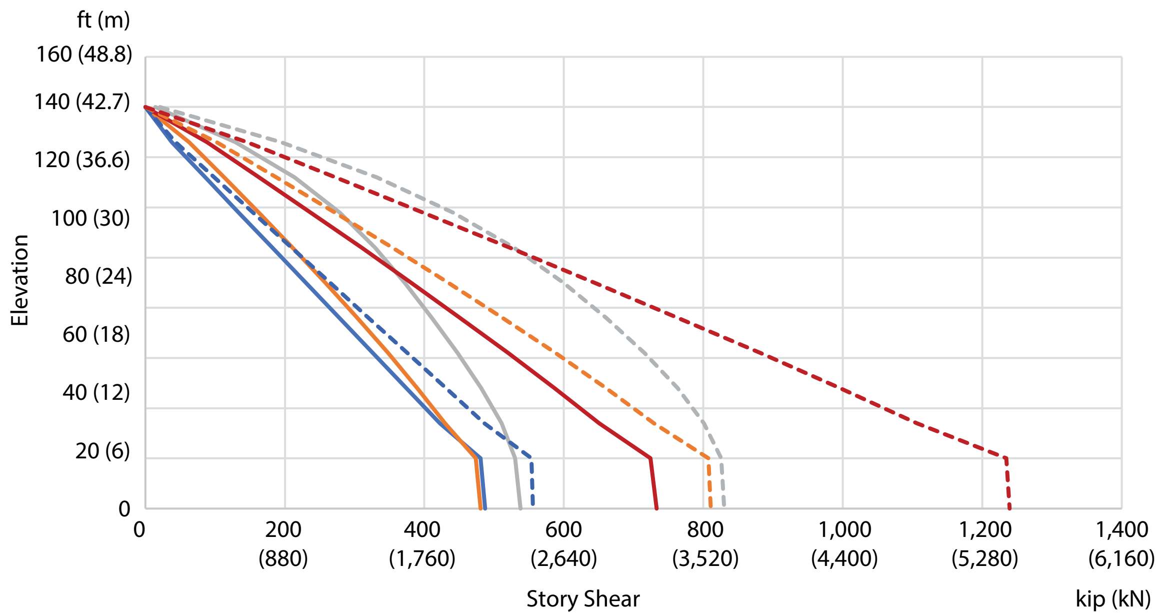


Figure 21. Story shear (strength level) for Prototype Building 3.

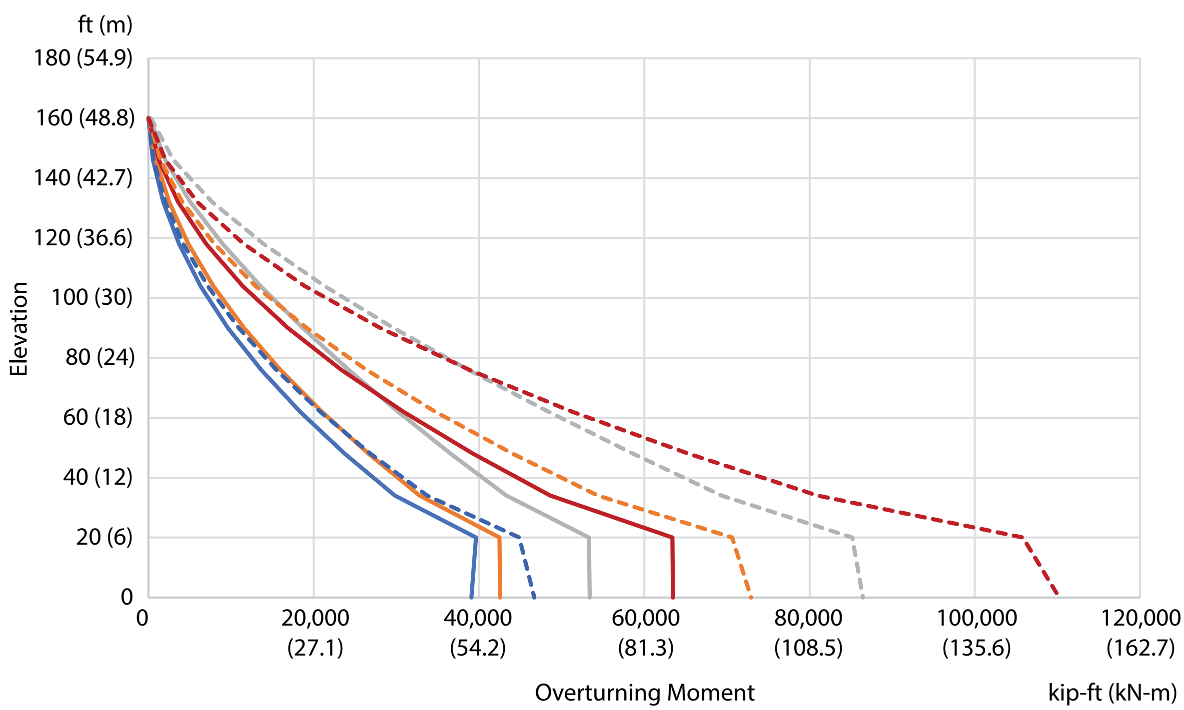


Figure 22. Overturning moment (strength level) for Prototype Building 3

5.4 Link Beam Stresses

The link beam shear stress diagrams are shown in figures 23 through 25. These figures show the increase in link beam shear stresses for each prototype building as a result of the updated provisions in IBC. The stresses are all well below the limit of 10√(f′c), which is the maximum level of shear permitted for typical designs.

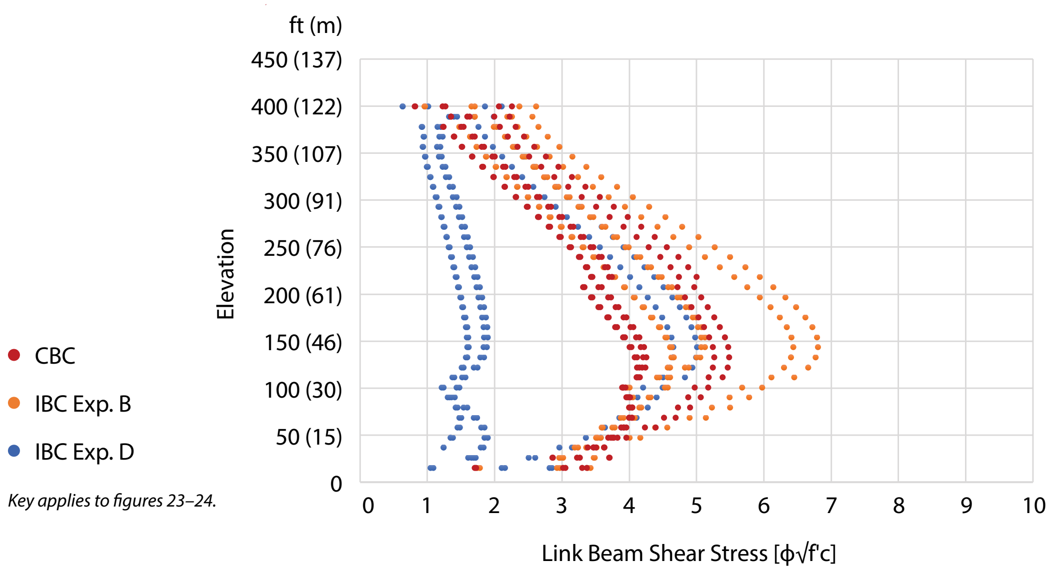


Figure 23. Link beam shear stress for Prototype Building 1.

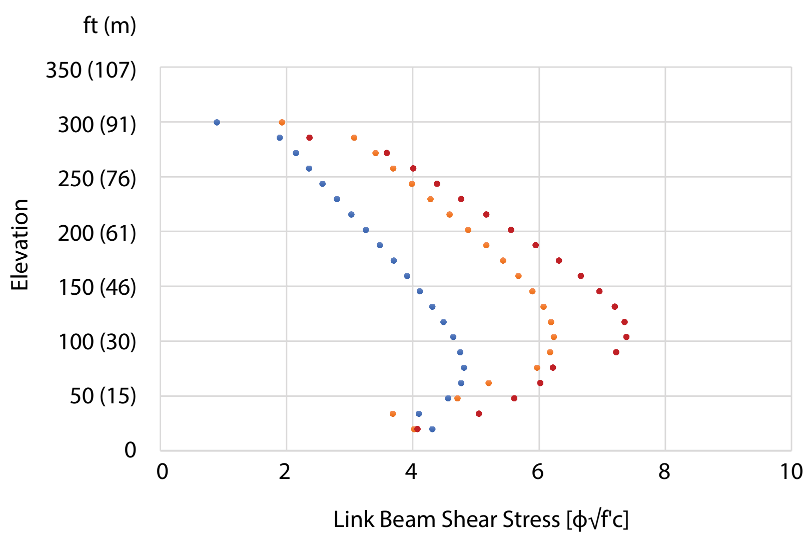


Figure 24. Link beam shear stress for Prototype Building 2.

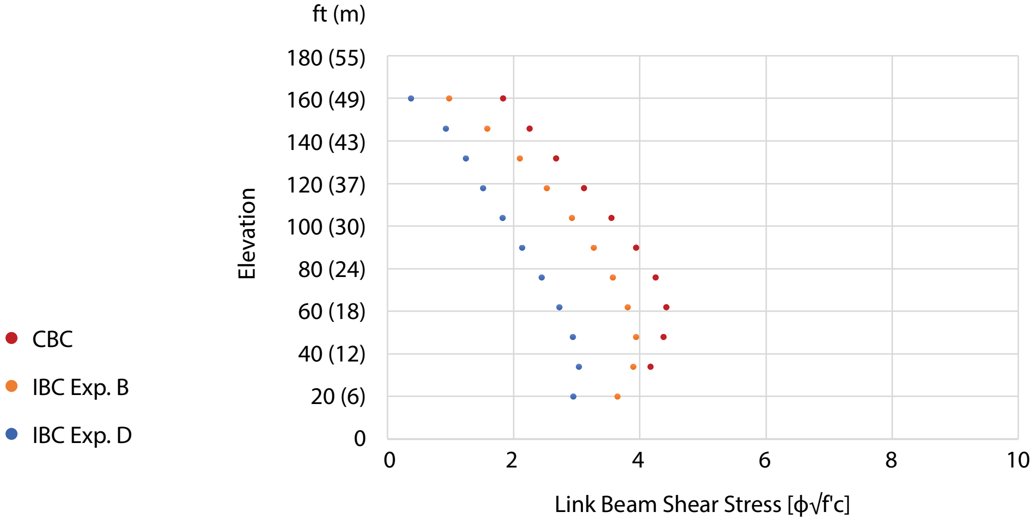


Figure 25. Link beam shear stress for Prototype Building 3.

6.0 Foundation Design Comparison

6.1 Design Soil Profile

GEI Consultants provided a typical design soil profile for the Chicago West Loop neighborhood, which was used to design the foundations for each of the prototype buildings (see Figure 26). The minimum depth for the bottom of caissons was determined to be 60 feet (18.3 meters), corresponding with the elevation of the Tinley Moraine layer. However, for prototype buildings 1 and 2, the caisson depth was increased from 60 to 78 feet (18.3 to 23.8 meters) to provide the required higher bearing pressure for gravity loads and more caisson length to counteract uplift.

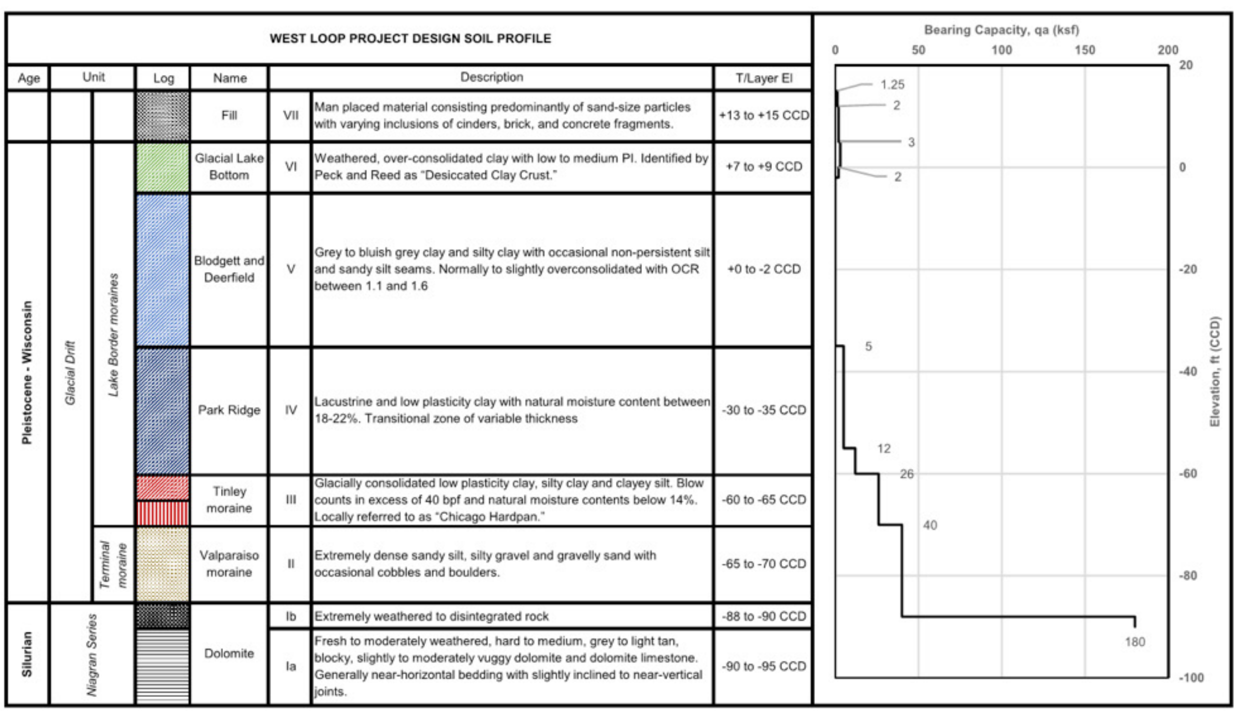


Figure 26. Chicago West Loop Area Design Soil Profile.

6.2 Foundation Analysis and Design

6.2.1 Foundation Design Characteristics

Belled caissons are utilized for the foundation type to support all three prototypes. The foundations are designed with a concrete compressive strength of 6500 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 $0.25f'_c$. 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 $0.30f'_c$. Additionally, a minimum reinforcement ratio of 0.005 is used for caissons.

6.2.2 Foundation Results

The foundation design (see Figure 27) consists of one caisson below each column. For the cores, caissons are placed at each corner (Location A). Where required, intermediate core caissons are added between the corner caissons (Location B). The difference in volume of concrete for CBC and IBC for each prototype building is illustrated in Figure 30.

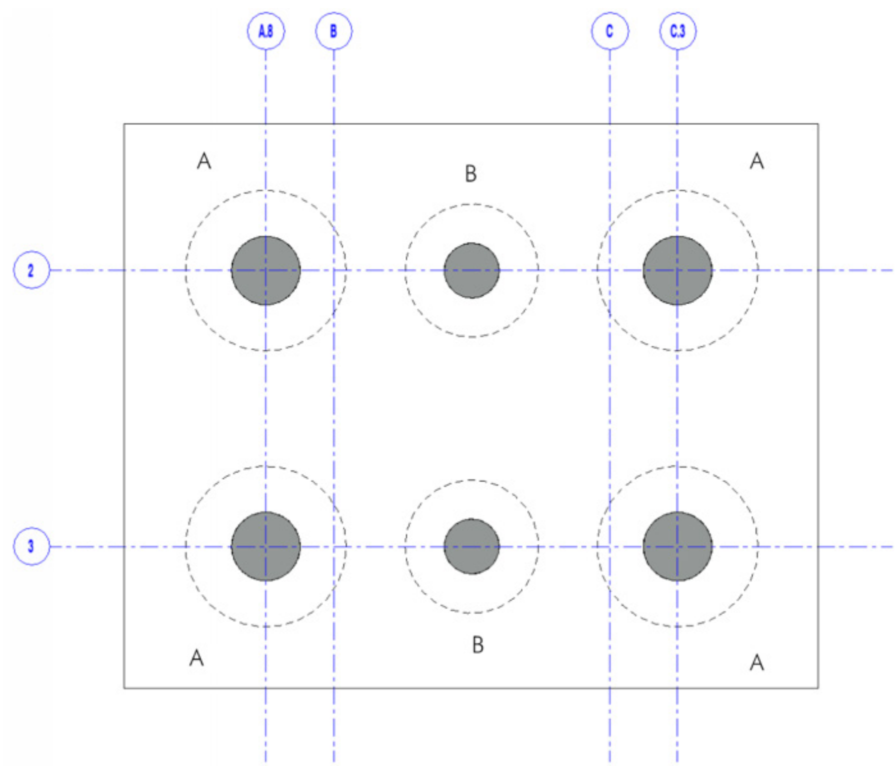


Figure 27. Typical caisson layout below core of prototype buildings.

7.0 Structural Quantity and Cost Summary

7.1 Structural Quantities

Figures 28 and 29 show the concrete and steel reinforcing quantities of the building core of each prototype building and resulting differences between the CBC and IBC designs. Figures 30 and 31 show the concrete and steel reinforcing quantities of the core caissons for each prototype building, as well as the resulting difference between the CBC and IBC designs.

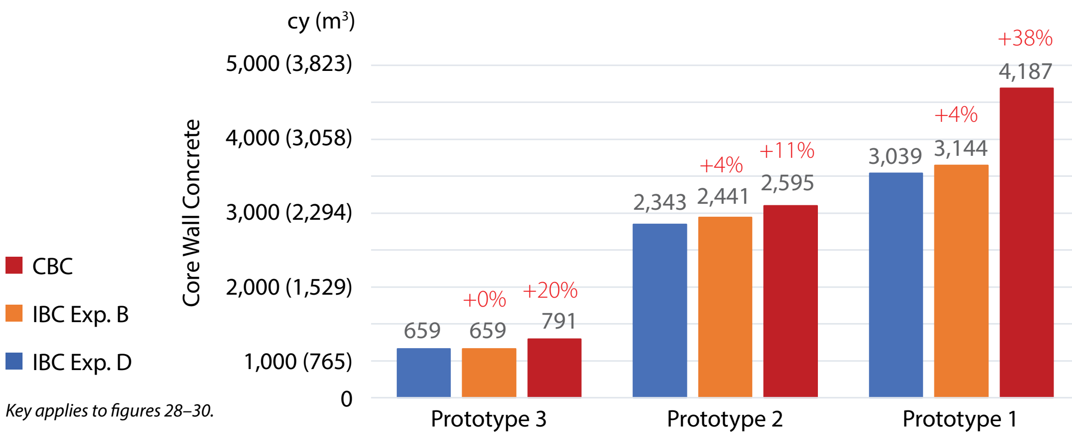


Figure 28. Concrete quantities for the core of each prototype building based on IBC and CBC.

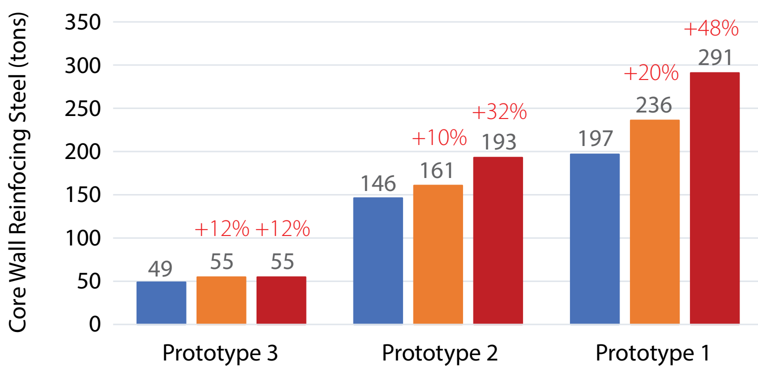


Figure 29. Reinforcing steel quantities for the core of each prototype building based on IBC and CBC.

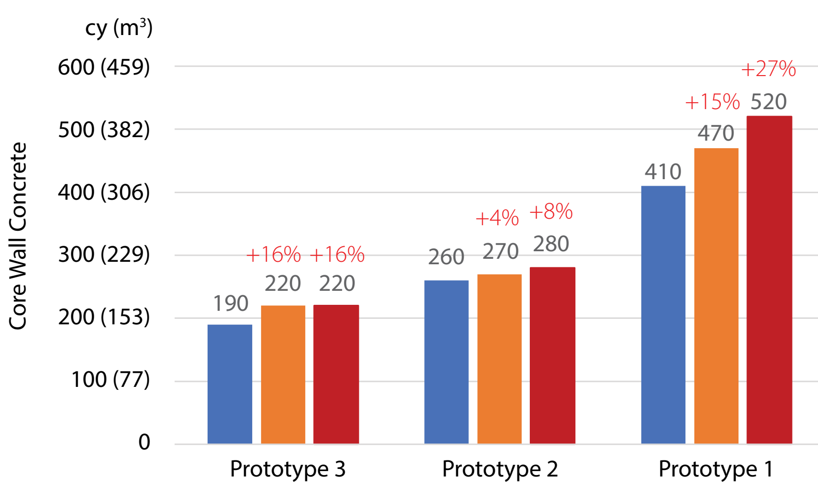


Figure 30. Caisson core concrete quantities for each prototype building based on IBC and CBC.

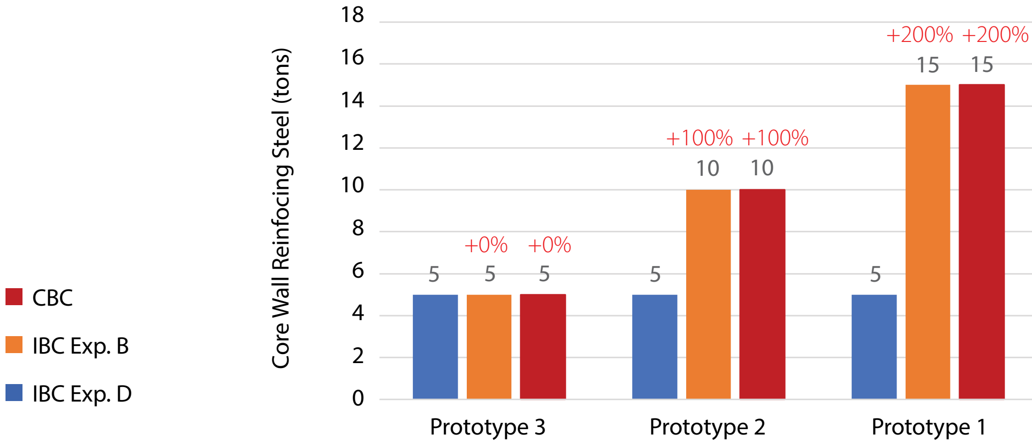


Figure 31. Core caisson reinforcing steel quantities for each prototype building based on IBC and CBC.

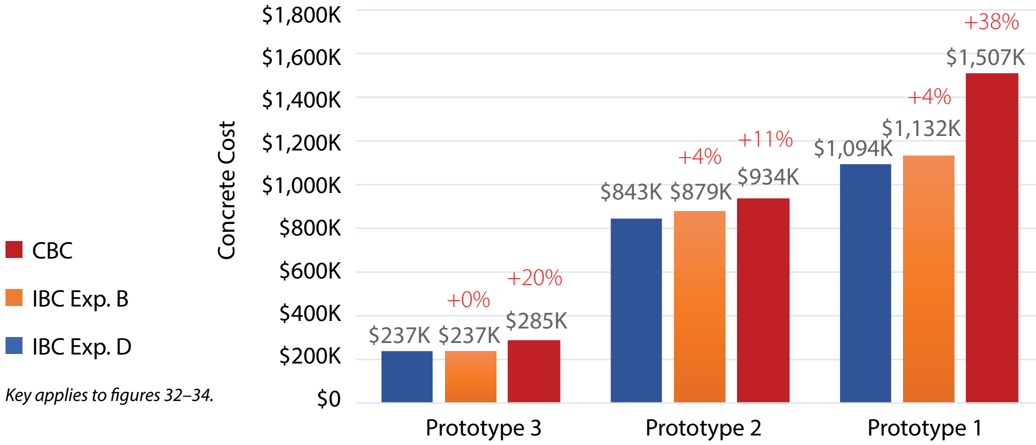
7.2 Cost Comparison

In order to understand the cost effects, two Chicago-based contractors provided unit costs for comparisons. Based on the calculated structural quantities and cost for each prototype building (see Section 7.1) cost differentials were approximated. Additionally, these cost differentials were compared to total building structural cost for each prototype.

Figures 32–36 illustrate the differences in cost of structural quantities for each prototype building based on the estimated values of the structural components listed in Table 9.

Structural/Material Component		Estimated Unit Cost
Superstructure	Concrete	\$360 / cu yd (\$275/m^3)
	Reinforcing steel placement	\$2,500 / ton (\$2,268/metric ton)
Caisson Foundation	Shaft Excavation	\$5.00 / cu ft (\$0.15/m^3)
	Bell Excavation	\$15.00 / cu ft (\$0.45/m^3)
	Caisson Concrete	\$175.00 / cu yd (\$134/m^3)
	Caisson Reinforcing Steel	\$2,500 / ton (\$2,268/metric ton)

Table 9. Estimated material unit rate costs.



Key applies to figures 32–34.

Figure 32. Core concrete cost for each prototype building based on IBC and CBC.

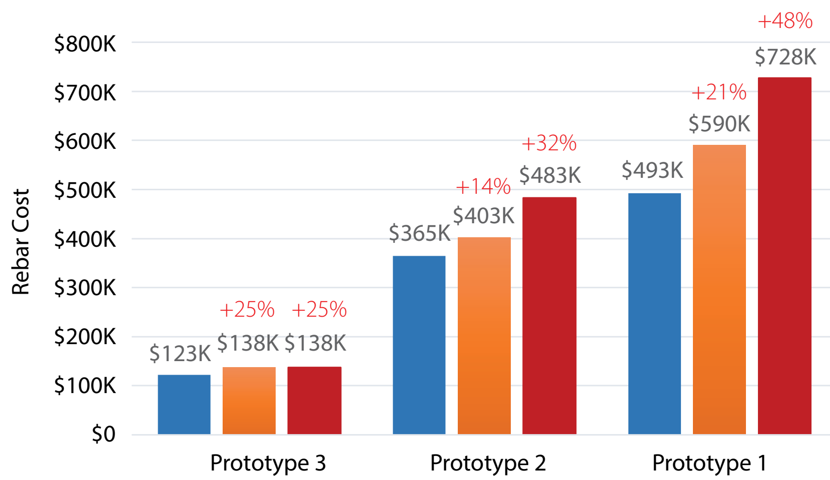


Figure 33. Core reinforcing steel cost for each prototype building based on IBC and CBC.

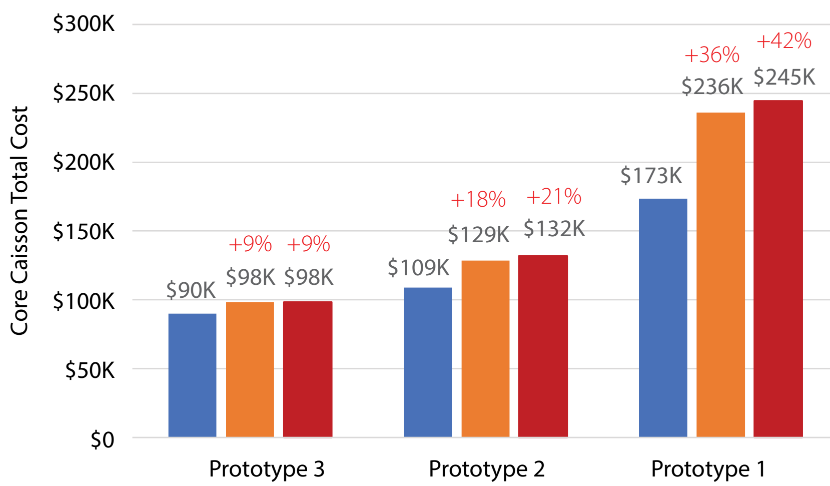


Figure 34. Total (core) caisson costs for each prototype building based on IBC and CBC.

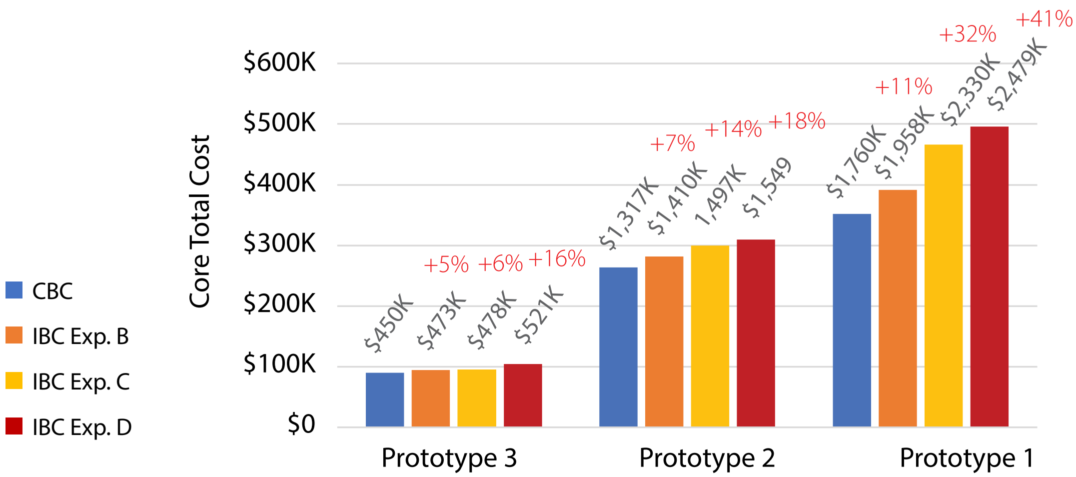


Figure 35. Total (core) caisson costs for each prototype building based on IBC and CBC.

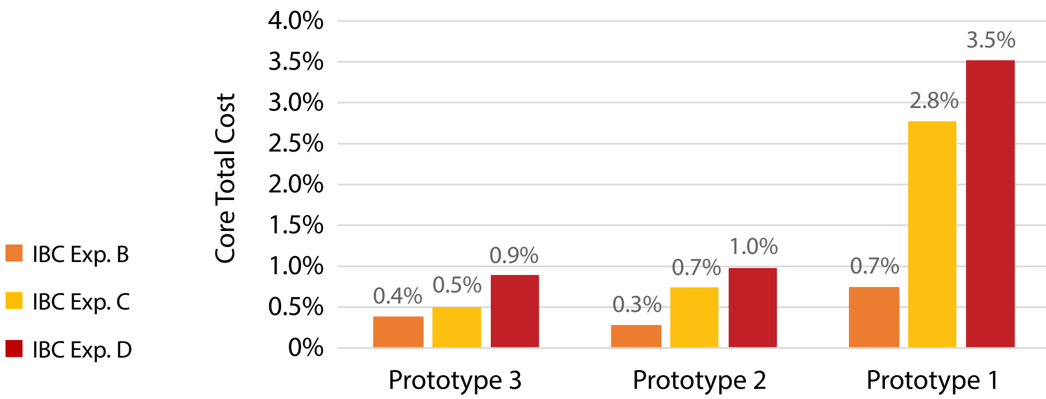


Figure 36. Total (core) caisson costs for each prototype building based on IBC and CBC.

8.0 Conclusion

The adoption of the 2019 CBC will bring Chicago in line with widely adopted national standards. The lakefront of Chicago results in 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 the increase in structural cost will generally not be significant except when construction is closer to 400 feet (122 meters) with lakefront exposure. Project teams should consider impact of structural premiums to projects and 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.

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About the CTBUH

The Council on Tall Buildings and Urban Habitat (CTBUH) is the world's leading resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities. Founded in 1969 and headquartered at Chicago's historic Monroe Building, the CTBUH is a not-for-profit organization with an Asia Headquarters office at Tongji University, Shanghai; a Research Office at Iuav University, Venice, Italy; and an Academic Office at the Illinois Institute of Technology, Chicago. CTBUH facilitates the exchange of the latest knowledge available on tall buildings around the world through publications, research, events, working groups, web resources, and its extensive network of international representatives. The Council's research department is spearheading the investigation of the next generation of tall buildings by aiding original research on sustainability and key development issues. The Council's free database on tall buildings, The Skyscraper Center, is updated daily with detailed information, images, data, and news. The CTBUH also developed the international standards for measuring tall building height and is recognized as the arbiter for bestowing such designations as "The World's Tallest Building."

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