Effects of Increased Wind Loads on Tall Buildings

Long-term global warming and climate change may increase wind loads, which may have negative effects on the performance of existing tall structures.

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A recent report accepted by most nations of the world, and supported by most scientists in the United States, stated that "emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate."[1] In Boston, Massachusetts, the average annual temperature could increase by as much as 6 to 10°F by 2090. The lower limit increase in annual average temperature would make Boston's climate similar to that of present-day Richmond, Virginia. The higher temperature increase would make Boston's average temperature more like that of Atlanta, Georgia.[2] Other expected changes in metropolitan Boston's climate due to this warming are increased precipitation and a continued rise in sea level. The likelihood and speed of extreme winds may also increase and, thus, wind loadings on tall structures may also be increased.

To analyze the possible effects of increased wind loads due to climate change on tall buildings in Boston, a finite-element building model was used. This model represented an idealized representation of a fifty-story tall, slender structure on a shallow continuous concrete mat foundation. The frame was assumed to be a moment resisting steel frame with concentric bracing at the core for lateral resistance to wind forces. The assumed subsurface conditions, typical of the original colonial Boston peninsula, consisted of dense glacial till capable of supporting the large loads of a tall structure.

Introduction

Metropolitan Boston has experienced a number of periods of active construction and expansion over the past three hundred years, each producing some unique elements of urban infrastructure. Johnson notes that some of the buildings that have survived from the 1700s were built on solid ground and were

TABLE 1.
A Comparison of the Model Fifty-Story Frame to Existing Structures

Criteria	Australia: Melbourne Central	Japan: Hamamatsu ACT Tower	Texas: Four Allen Center	Boston: Fifty-Story Frame Model
Height (ft)	692	695	691	600
Stories	54	47	50	50
Levels Below Grade	3	2	2	2
Frame Material	Steel with concrete core	Steel	Steel	Steel
Typical Live Load (psf)	80	100	50	77
Basic Wind Velocity (mph)	112	67	92	90
Allowable Lateral Deflection (ft)	0.33	3.5 (or H/200)	1.7 (or H/400)	1.2
Foundation Type	Combined mat & footings	Piles	Mat	Mat
Story Height (ft)	13	10	13	12
Beam Span (ft)	38	33	40	25
Beam Depth (in)	21	27.5	25	31.7
Beam Spacing (ft)	10	10	15	25
Slab (in)	4.75	7	3.25	4

probably supported on granite footings.[3] Other buildings, such as Faneuil Hall and Quincy Market, had to be supported on timber pilings driven through fill and underlying mud. The Back Bay was filled during the second half of the nineteenth century and experienced the construction of many three- to six-story townhouses as well as some large public buildings such as Trinity Church, Horticultural Hall and the Copley Square Library. Most of these structures were founded on untreated timber piles that were driven through shallow fill and organic layers to underlying sands and clays. The twentieth century brought little major new urban construction until the 1960s. The construction of the Prudential Center at about this time began a period of active construction that has continued to this day. Currently, the tallest building in Boston is the 788-foot-high, sixty-story John Hancock Building, which was built in 1969.[3]

A structure of the size and foundation type selected for this study, a fifty-story office tower founded on a concrete mat, must be supported on very strong soil or rock. The glacial till in Boston is capable of supporting loads from such large structures, with allowable bearing pressures as large as 10 tons per square foot (tsf).[4] Several different types of framing systems are associated with tall structures. Braced frames rely on the axial stiffness of the framing members to resist lateral loads. The geometry of these systems is often governed by the specific needs for access and openings in a structure. Moment resisting frames consist of rigidly connected beams and columns. The resistance to lateral loads in these framing systems comes from the flexural stiffness of the framing members. Although moment resisting frames are beneficial for architectural purposes, they become inefficient for structures exceeding twenty to thirty stories in height due to the quantity of material necessary to obtain adequate stiffness.[5] In order to achieve adequate lateral resistance to loads brought on by wind or seismic activity, braced moment resisting frames are commonly used in forty- to fifty-story buildings.[5] For this study, a moment resisting steel frame with concentric bracing at the core was used. This combined system provided sufficient lateral stiffness for the fifty-story building model. Table 1 summarizes the features of this structural model and shows that it is characteristic of some existing structures around the world as described by Kowalczyk.[5]

Boston lies in a region susceptible to hurricanes, which are tropical storms with Saffir/Simpson Hurricane Scale Category 1 winds ranging from 74 to 95 miles per hour (mph) and Category 5 winds greater than 155 mph. The highest sustained 1-minute wind speed ever recorded from a hurricane in New England was 121 mph; the highest gust was 186 mph. Both of these were measured during the 1938 Great New England Hurricane at the Blue Hill Observatory in Milton, Massachusetts, located on a 627-foot-high mountain about 10 miles south of Boston.[6] Because of the inability to accurately model hurricanes in climate change models (Generalized Circulation Models, or GCMs), it is not possible to state with certainty how hurricane formation and associated wind speeds will change in the future. One of the most recent international panels of climate experts stated that there is not a consensus on changes in the intensities of tropical storms under climate change.[7] An earlier summary in 2000 stated that there is the possibly of increased intensities but not enough knowledge to state if the increases are unlikely, likely or very likely.[8] One experimental model study working under a scenario of a 1 percent annual increase in CO_2 reported that by approximately 2095 maximum hurricane surface wind speed in the northwestern tropical Atlantic region could increase by 3.3 to 5.0 percent.[9]

For this study, sensitivity analysis was used on wind velocities to determine if there should be concern for the integrity of tall buildings due to changing wind loads in the future. Because there is great uncertainty on how wind loads on tall buildings in Boston may change in the future, a wide range of possible wind speed increases of 10, 20, and 30 percent in design wind speeds were used in the sensitivity analysis.

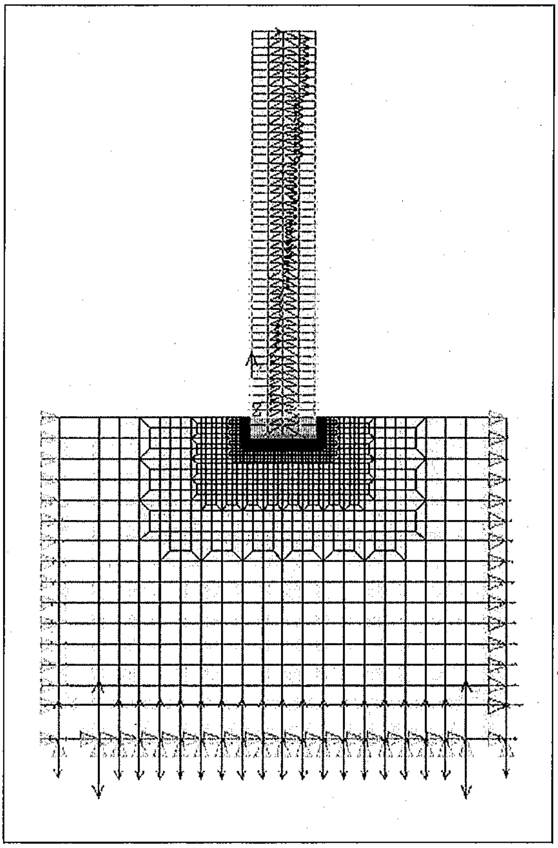


FIGURE 1. Computer model of the fifty-story building with a mat foundation on soil.

Modeling

The finite element software selected for modeling this structure was ANSYS, a general-purpose finite element code. The models built in ANSYS were verified by comparison with published theoretical solutions and with another finite element code, PLAXIS.[10] The soil was represented by plane strain elements, while the building was represented by frame elements. Figure 1 shows the finite element model of the fifty-story building, foundation mat and soil. The structural system consisted of steel framing with core bracing similar to that of a Pratt brace. The floor height was assumed to be 12 feet, the framing material to be steel and the flooring system to be metal decking with a concrete slab 4 inches thick. The foundation system was an 8-foot-thick

TABLE 2.
Material Properties for the ANSYS Model

Material	Property	Full Values (U.S. Units)	Scaled Values (U.S. Units)
Concrete Beams in Basement	γ	150 pcf	6 pcf
	ν	0.15	0.15
	E	580,000,000 psf	23,200,000 psf
Steel Beams & Columns	γ	490 pcf	19.6 pcf
	ν	0.30	0.30
	E	4,176,000,000 psf	167,040,000 psf
Concrete Beams in Basement	γ	150 pcf	6 pcf
	ν	0.15	0.15
	E	580,000,000 psf	23,200,000 psf
Concrete Mat Foundation	γ	150 pcf	150 pcf
	ν	0.15	0.15
	E	580,000,000 psf	580,000,000 psf
Soil	γ	130 pcf	130 pcf
	ν	0.25	0.25
	E	10,000,000 psf	10,000,000 psf

reinforced concrete mat. This combined soil, foundation and structural model was created to study the soil-structure interaction for various wind speeds. It allowed for more realistic response calculations since it took into account the flexibility of the foundations and the supporting soil. The soil-structure interaction model also influenced the structural displacements and internal forces.

Structural response to wind loads is ordinarily performed in the direction of the principal axes of buildings with rectangular footprints. The building was transformed into two dimensions for gravity and wind analysis, and the spacing of one bay was assumed to be 25 feet for the purpose of this transformation. Structural properties and loadings were adjusted to represent a unit two-dimensional slice of the three-dimensional structure. The unit slice of the fifty-story building model did not require any scaling for continuous components (e.g., mat foundation and soil) and distributed loadings in the third direction. However, properties of discrete components (e.g., beams and columns) and concentrated loadings required scaling by the inverse of the spacing used in the third direction. The stiffness of beams and columns was based on elastic modulus *(E)* and area *(A)* for axial loading and elastic modulus and moment of inertia *(I)* for bending. The stiffness of the building's beams and columns, located at the 25-foot bay spacing, were scaled by reducing by a factor of 1/25 the one common stiffness parameter, the elastic modulus. Doing so automatically reduced the bending stiffness *(EI)* and axial stiffness *(EA)* without adjusting the moment of inertia or cross-sectional area of each member. Also, the material density for the discrete members was scaled by the same 1/25 factor so that full self-weight was applied consistent with the scaling performed over each 25-foot bay. Table 2 summarizes the assumptions made for the material properties.

Loading conditions were based on the 1997 Massachusetts Building Code.[4] The loads used in this analysis included dead, live and wind. Seismic loads were not considered in order to simplify the analysis and to focus on the effects of increased wind loads. Dead load

TABLE 3.
Summary of Dead & Live Loads

Dead Loads (psf)		**Live Loads (psf)**	
Floor	50	Offices	50
Ceiling/Mechanical	10	Lobbies	100
Partition	20	Corridors	80
Steel	16	Average	77
Total Applied	96	Total Applied	77
Total Dead & Live Load Applied = 96 + 77 = 173 psf			

included the weight of the framing, flooring, ceiling and mechanical, and partition load (assumed to be office space). The live load was taken directly from the Massachusetts Building Code (Table 1606.1) and was assumed to be representative of the typical loads found in offices, office lobbies and corridors. The dead and live loads applied to the structure, as uniformly distributed loads, are summarized in Table 3. These loads were not scaled for the two-dimensional transformation because they were continuous.

For wind loads, the Massachusetts Building Code separates the state geographically into three zones of exposure with the Boston metropolitan area falling into Zone 3. The code further separates these zones into three exposure categories. They include Exposure A (for the centers of large cities), Exposure B (for towns and cities) and Exposure C (for open, level terrain). These wind load zones are based on a "fastest-mile" wind velocity at 30 feet above the ground surface as described in Section 1611.3 in the Massachusetts Building Code. The "fastest-mile" wind velocity is based on statistical data for each region of the United States.

The reference wind loads, unaffected by global climate change, were calculated from the Massachusetts Building Code (Table 1611.4) assuming Zone 3 for the Boston metropolitan area, and Exposure B for towns and cities as may be typical for design of a structure of this type. The wind loads were calculated by multiplying the Massachusetts code wind pressures by the area exposed to wind (a typical floor height of 12 feet by one bay [or 25 feet]). The resulting point loads were scaled by 1/25 to transform for the two-dimensional analysis and applied to the corresponding floors.

Three climate change scenarios were analyzed by increasing the wind velocity. Current Massachusetts building code defines values of wind pressure based on a reference wind velocity (V_{30}) of 90 mph. This parametric study considered the effects of increased wind pressures based on increased wind speeds of 10, 20 and 30 percent. While there is some uncertainty about the magnitude of any changes in wind speeds due to long-term climate change, this range of wind velocities was chosen to determine if there should be concern for the integrity of tall buildings due to changing wind loads in the future. Since the Massachusetts code does not offer a relationship between wind velocity (V) and pressure (p), the general design equation was used:[11]

$$p = CV^2 \qquad 1$$

In Equation 1, C is an empirical coefficient. Figure 2 on the next page graphs this equation. Table 4 (on page 11) summarizes the wind loads calculated by the 1997 Massachusetts Building Code and the increased corresponding values using Equation 1. One twenty-fifth of these values were applied to the unit slice model of the fifty-story building.

Method of Analysis

The complete structure, foundation and soil model is shown in Figure 1. Boundary condi-

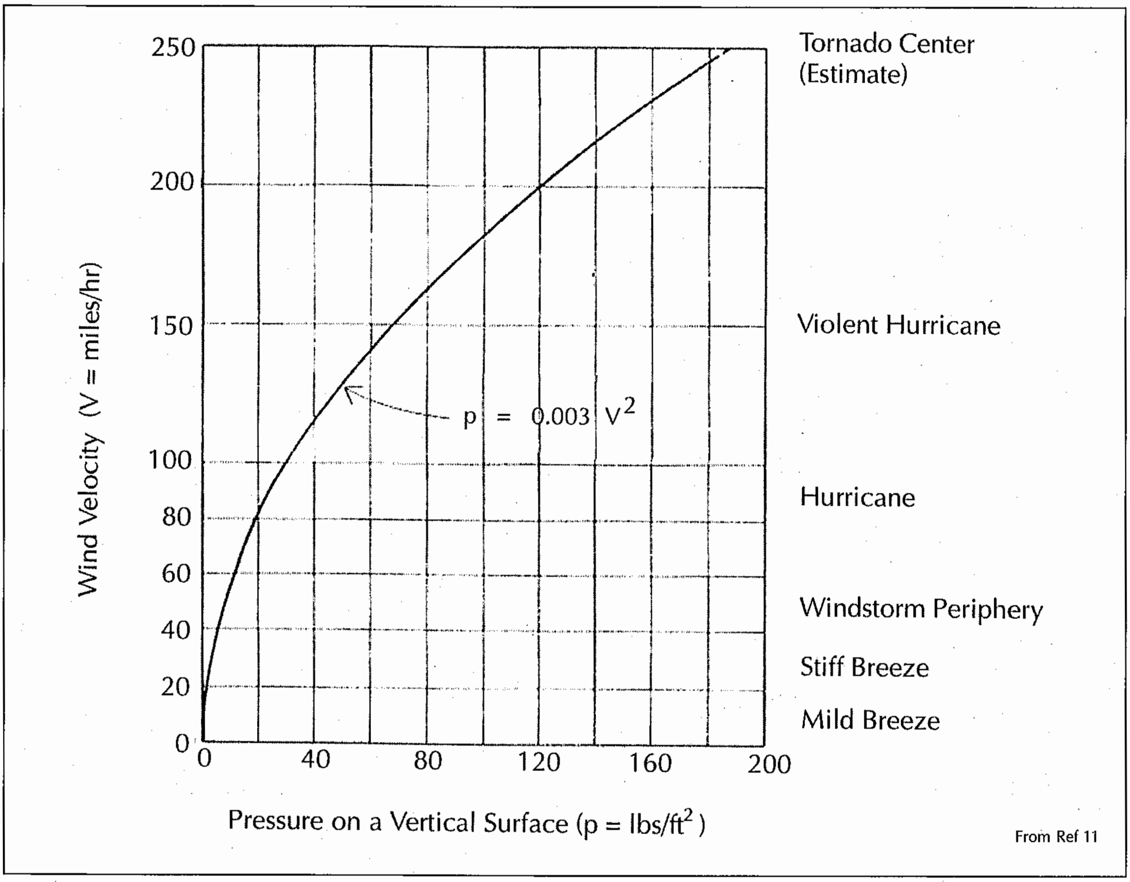


FIGURE 2. Wind pressure and velocity relationship.

tions at the lateral extents of the model permitted vertical soil movement. The bottom boundary condition prevented horizontal and vertical soil movements. A detailed section of the lower levels and foundation system of the ANSYS model is shown in Figure 3. It illustrates the areas of interest in the lower floors of the structure, basement garage, mat foundation and the supporting soil that potentially may experience higher stresses as the wind speed increases.

The method of analysis approximately modeled the stress state in the ground, beginning with initial geostatic stresses, followed by the stress changes caused by the construction of the foundation walls, excavation of soil, construction of the foundation mat and building, and application of the wind loads. Initially, the building elements were deactivated and all materials properties of the concrete mat were set equal to soil. Proceeding in this way helped model the pre-construction condition to generate the initial, or geostatic, stresses in the soil. This initial phase (to generate geostatic stresses in the soil) was followed by six more stages of excavation and construction:

- Phase 1: Activate the right foundation wall.
- Phase 2: Activate the left foundation wall.
- Phase 3: Excavate the soil between the walls.
- Phase 4: Activate the concrete mat.
- Phase 5: Activate structural members, dead and live loads.
- Phase 6: Activate wind loads on structure.

Phases 1 and 2 changed the material properties of the elements representing the right and left foundation walls from soil to concrete. Phase 3 deactivated the soil elements between the walls to simulate a soil excavation. Phase 4

TABLE 4.
Applied Wind Loads for Massachusetts Building Code Base Values & Increased Wind Speeds

Wind Speed Scenarios	Code Wind Speeds		Increased Wind Speeds					
			10%		20%		30%	
Floors/Units	**(lb)**	**(kN)**	**(lb)**	**(kN)**	**(lb)**	**(kN)**	**(lb)**	**(kN)**
1-8	252	1.12	305	1.36	363	1.61	426	1.89
9-12	312	1.39	378	1.68	449	2.00	527	2.34
13-16	360	1.60	436	1.94	518	2.30	608	2.71
17-21	408	1.81	494	2.20	588	2.62	690	3.07
22-26	444	1.98	537	2.39	639	2.84	750	3.34
27-34	492	2.19	595	2.65	708	3.15	831	3.70
35-42	552	2.46	668	2.97	795	3.54	932	4.15
43-49	612	2.72	741	3.30	881	3.92	1,034	4.60
50-Roof Gets Half	306	1.36	370	1.65	440	1.96	517	2.30

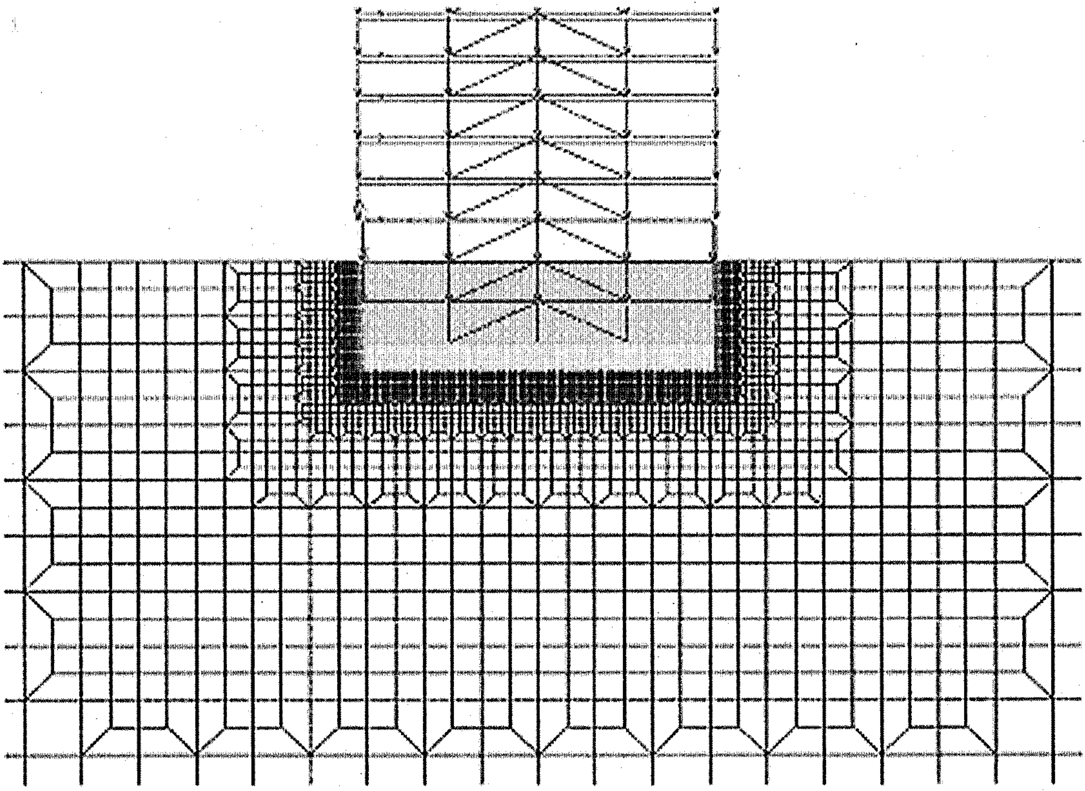


FIGURE 3. Detail section of the ANSYS foundation model and lower floors of the structure.

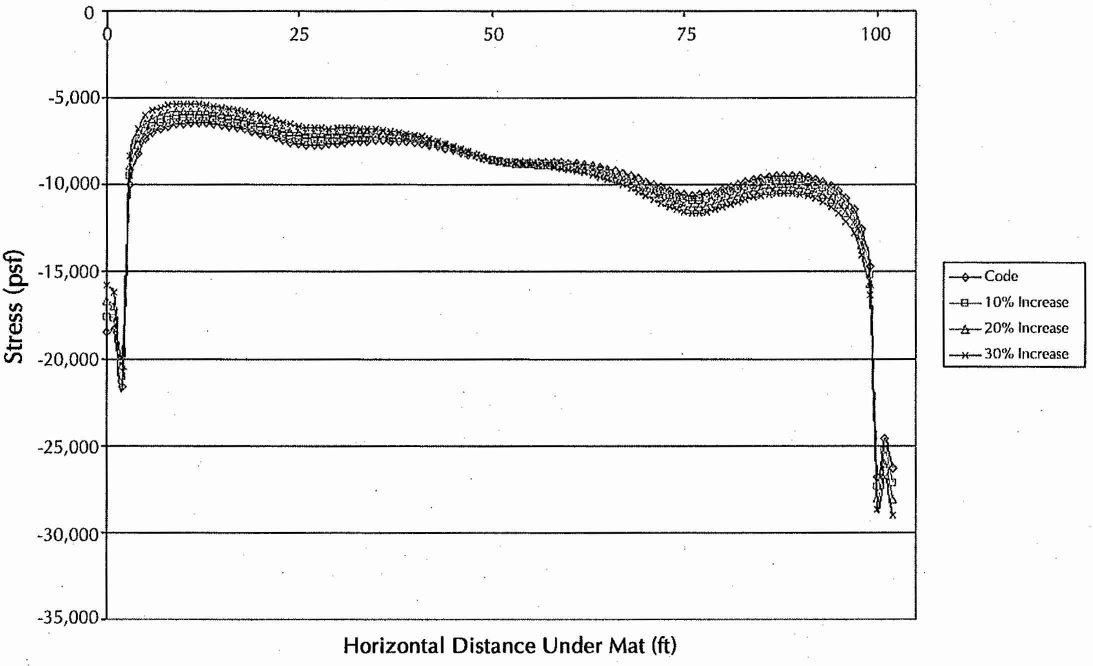


FIGURE 4. The effect of increased wind loads on vertical contact stresses.

reactivated the soil elements in the vicinity of the building's mat foundation and changed their material properties to concrete. Phases 1 through 4 neglected excavation support issues and used a linear elastic soil model in order to simplify the analyses. The foundation walls and mat were "wished" into place. Phase 5 activated the building elements and applied the dead and live loads. The final phase (Phase 6) applied the wind loads to the structure. Note that the effects of increased soil stresses and deformations due to climate induced wind load changes must be further evaluated by additional studies (which are beyond the scope of this research) that incorporate inelastic soil models.

Results

Vertical stress distributions 1 foot below the mat foundation are shown in Figure 4. The x-axis shows the horizontal distance under the mat as measured from the windward edge of the building. The stress concentrations at the 25-, 50- and 75-foot markers coincided with the building's column locations. For all wind loading cases, the soil contact stresses were greater on the leeward (toe) side of the building than the windward (heel) side of the building. The increased wind loads increased the difference in vertical soil pressures from the windward to leeward side of the building. In the central region of the building, the soil stresses changed by less than 5 percent due to the 30 percent wind load increase over the from the Massachusetts Code reference values. In the exterior bays, the corresponding soil stresses changed by about 20 percent (or 2000 psf). The stress increases on the leeward side of the building were not large enough to overload the very strong foundation soils, which had allowable bearing capacities as large as 8 to 10 tsf by the Massachusetts Building Code (Table 1201). The decreased stresses on the windward side of the building were still positive (compressive) so that there was no dangerous uplift condition.

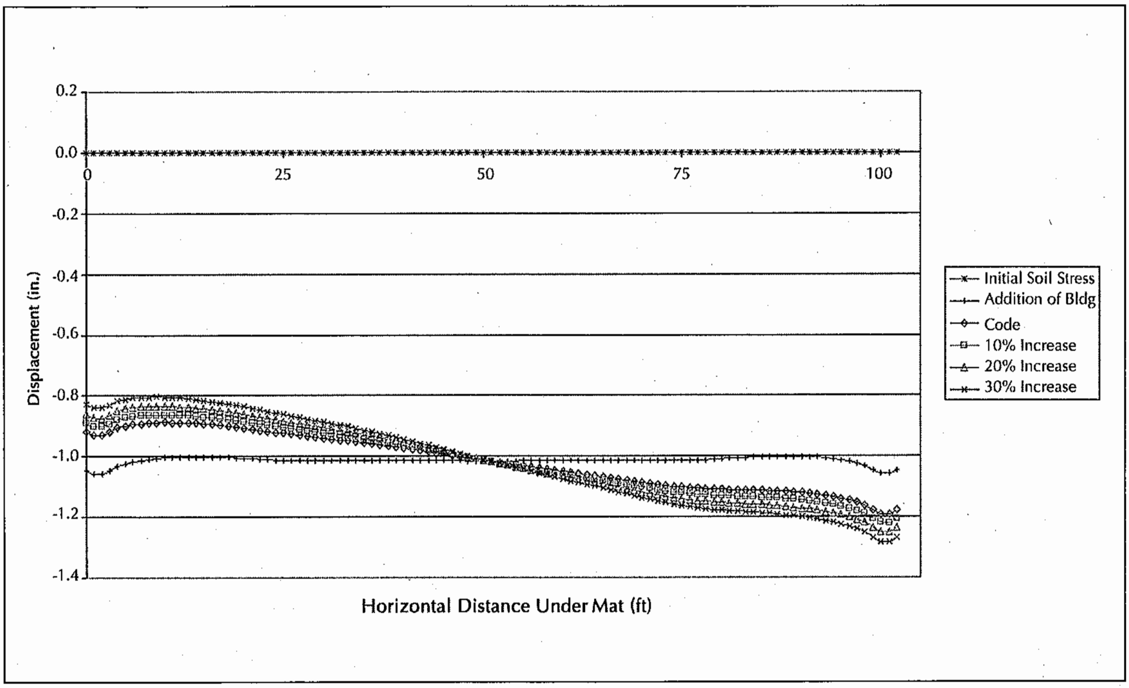


FIGURE 5. The effect of increased wind loads on vertical displacements.

Figure 5 shows the foundation displacements due to two phases prior to the addition of the wind loads. The displacements were all referenced to the initial geostatic stress condition due to the self-weight of the soil. The addition of the building weight, dead load and live load caused a uniform 1-inch vertical displacement (settlement). Finally, the code, 10, 20 and 30 percent wind loads changed the settlement distribution. The code wind loads changed the settlements by about 15 percent, with the settlements decreasing on the windward side to a minimum of about 0.9 inches and increasing on the leeward side to a maximum of about 1.2 inches. The 30 percent increase of the code wind values further changed the foundation settlements so that they varied from a minimum of 0.8 inches (windward) to a maximum of about 1.3 inches (leeward). This increased tilting of the foundation mat provided a secondary contribution to the building's structural response, especially building sway.

Figure 6 compares the computed lateral deflections (sway) caused by the different wind load cases. The 30 percent increased winds produced a large sway deflection with a maximum value of 2.3 feet, which is almost double the sway calculated using the wind pressures given by Massachusetts Code that resulted in a maximum sway of 1.2 feet. These large wind-induced sways potentially could cause human discomfort and costly architectural damage. They could also cause cracking and spalling of fire protection materials from the surface of steel structural members leading to a reduction in protection against fire.

Figure 7 shows the bending moments in beams and columns of the first and second floors computed for each of the wind load cases. (The key inside Figure 7 shows the members of the frame selected for the presentation and discussion of building structural effects.) The moments in the columns increased by a maximum of 10 percent on the leeward side and decreased by a similar amount on the windward side as the wind loads increased. These changes were within the structural capacity of the columns. The changes in the beams' bending moments on the first floor were small and within the structural capacity of the beams. However, the greatest changes occurred in the second floor beams in Bay 4, where the bending moments

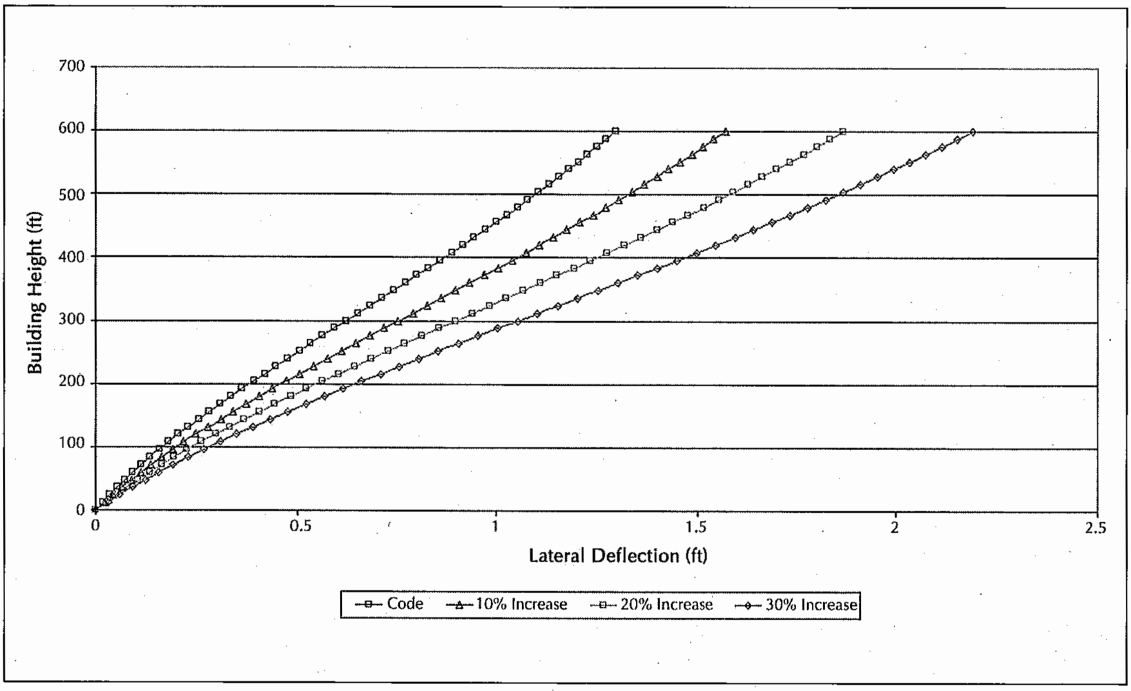


FIGURE 6. Lateral deflection of building center line for increased wind loads.

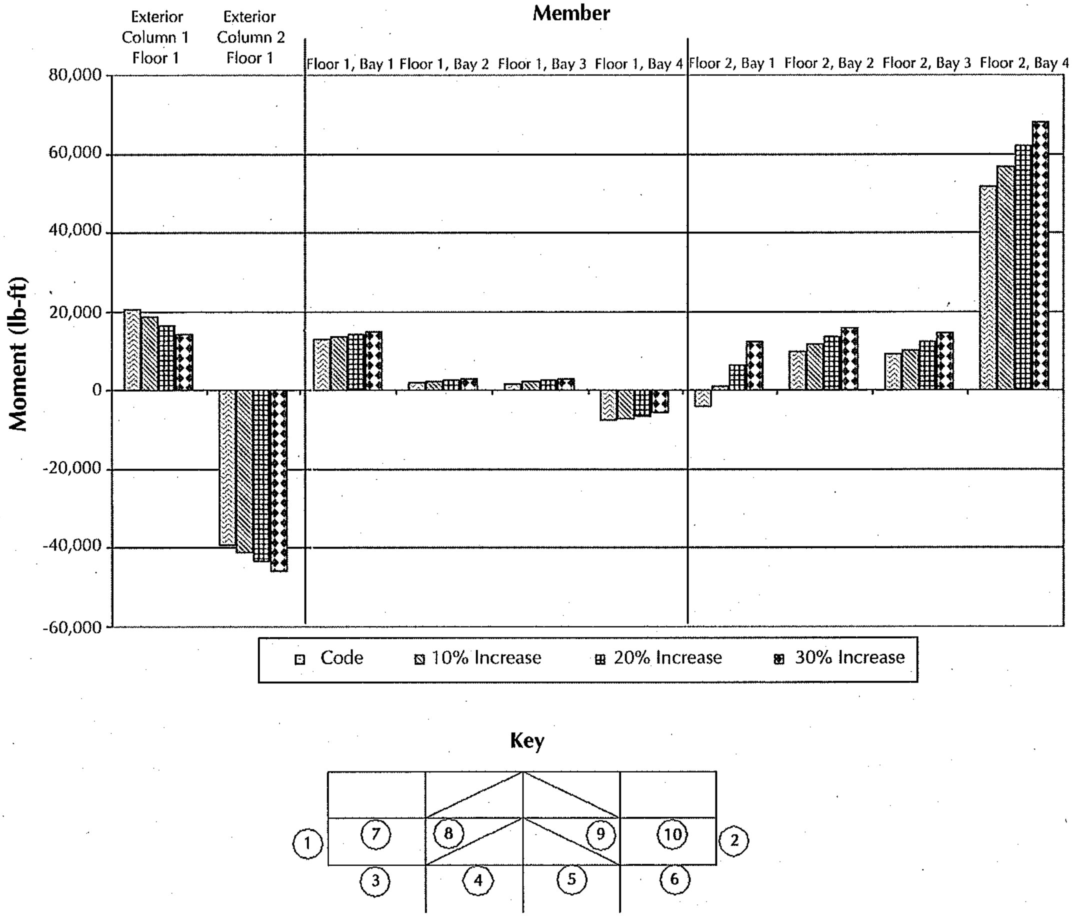
increased by about 30 percent as the wind loads increased, which represents a large reduction in the reserve capacity of the leeward beam elements and is cause for concern.

Conclusions

This study investigated the effects of increased wind loads due to climate change on a fifty-story building typical of large structures in the Boston metropolitan area. The effects of a 30 percent increase in design wind velocities over present Massachusetts Building Code requirements were evaluated. The increases of soil bearing stresses on the leeward side of the building were not large enough to overload the very strong foundation soils. The decreased soil bearing stresses on the windward side of the building were still compressive so that there was no dangerous uplift condition. This increased tilting of the foundation mat due to the wind load increases provided a secondary contribution to the building structural response, especially building sway.

The effects of a 30 percent increase in design wind velocities on building columns were small but bending moments increased significantly in the lower floors of the building, resulting in a large reduction in the reserve capacity of the leeward beam elements, which is cause for concern. The greatest effect of the increased wind load was an almost doubling of lateral deflections (sway) of the building. These large wind-induced sways potentially could cause human discomfort and costly architectural damage. They could also cause cracking and spalling of fire protection materials from the surface of steel structural members leading to a reduction in protection against fire. The structure might also experience increased cracking of non-structural architectural finishes, leading to increased maintenance costs.

These analyses in no way relate to an existing structure. Although a 30 percent wind speed increase significantly impacts the serviceability of the model building, the possible effects of climate change on wind speed may not produce changes that would be of this magnitude. In fact, some research indicates that there may be only a 3 to 5 percent wind speed increase in 2095.[9] On the other hand, this research presents initial conclusions that suggest these types of analyses will become important with changing climate conditions.



1. Exterior Column 1, Floor 1
2. Exterior Column 2, Floor 1
3. Floor 1, Bay 1
4. Floor 1, Bay 2
5. Floor 1, Bay 3
6. Floor 1, Bay 4
7. Floor 2, Bay 1
8. Floor 2, Bay 2
9. Floor 2, Bay 3
10. Floor 2, Bay 4

FIGURE 7. Bending moments in the first and second floors.

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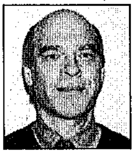

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