Comparative Analysis of the Wind Speeds and Wind Loads Requirements for Puerto Rico on the Last Three Decades

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Abstract *— This paper presents an analysis of the changes and differences of the wind load provisions between the Building Regulation No. 7 of Puerto Rico (amended in 1987) and the ASCE 7-88 through ASCE 7-16 and how they compare to the current Building Code of Puerto Rico. The comparison focuses on wind speeds, external pressures, and resulting external pressures considering factored actions (ultimate state design). As result of the analysis, it was observed a general tendency to increase the basic wind speed with the years, but since the load factor for wind loads in the 2010 and 2016 edition was reduced to 1.0 (wind loads are considered ultimate loads), the resulting factored pressures have been reduced as compared to the current code that follows the 2005 edition of the ASCE 7. To obtain similar pressures with the new standards that the ones obtained with the 2005 edition, the 3-second gust wind speed in Puerto Rico should be at least 183 mph. Considering the damages and structural failures observed just after the passing of Hurricane Maria in Puerto Rico, and the ones produced by Hurricane San Felipe in 1928, and due to the possibility of adopting new building codes such as the ASCE 7-16, we suggest that a code revision regarding the basic wind speed for Puerto Rico is necessary.*

Key Terms *— Hurricanes, Puerto Rico, Wind Loads, Wind Speeds.*

INTRODUCTION

In 2017, the island of Puerto Rico was pounded by the high winds and heavy rain of hurricane Maria, a high-end Category 4 hurricane that caused a lot of catastrophic damages to several structures, residential homes and infrastructural components such as utility poles and traffic signs, including the destruction of its previously damaged electrical grid. Figure 1 presents a satellite image of the hurricane, hours before making landfall over the Southeast of Puerto Rico. Maria is by far the strongest hurricane, with registered sustained winds greater than 150 mph, to make landfall in Puerto Rico since a Category 5 hurricane know as San Felipe the Second made land fall in 1928. At the time of the passing of hurricane San Felipe the Second, an anemometer at the office of the United States Weather Bureau in San Juan lost one of its cups just after recording a maximum velocity (the greatest velocity in 5 minutes) of 150 mph [1]. If the anemometer hadn't lost one of its cup at the Weather Bureau station, it would have registered winds not less than 190 mph [1]. The path of these two storms across Puerto Rico were almost identical. Figure 2 is an aerial view that shows homes that were left roofless in Puerto Rico, due to the strong winds brought by the hurricane.

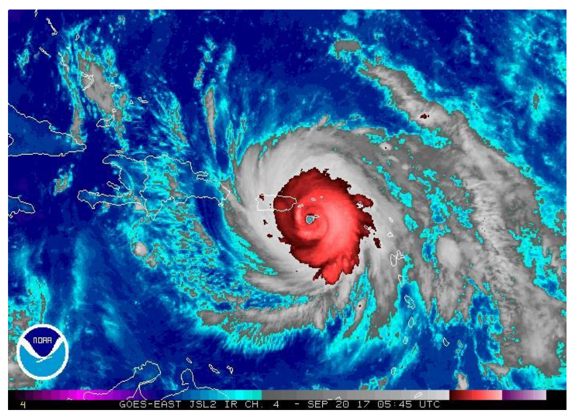

Figure 1
Hurricane Maria at its strongest September 20, 2017 (NOAA-OSPO)

These wind effects on building structures are important because it gives us a motive to investigate the reason behind these failures and to be able to improve the design and construction in Puerto Rico.

Since the highest wind speed of Hurricane Maria was greater than the 3-second gust wind speed under the current Puerto Rico Building Code [2], 2011 PRBC (145 mph) in which refers to the American Society of Civil Engineering Standard, ASCE 7-05 [3], a brief research was conducted to compare the wind load factors, the wind speeds and external wind pressure between the Building Regulation No. 7 [4] approved by the Puerto Rico Planning Board (Reglamento de Edificación – Reglamento de Planificación Núm. 7) which was amended in 1987, and the ASCE 7-88 through the ASCE 7-16 [3], [5]-[10].

First, we shall identify the changes to the wind provisions contained in the Building Regulation and in these later versions of the ASCE 7. Then we shall compare the wind provisions by calculating the ultimate external wind pressures for a building of 33 ft of height for an Exposure C and Exposure D for the ASCE 7 standard from 1988 to 2016 [3], [5]-[10]. Also, we shall compare these ultimate wind pressures with the 1987 Building Regulation of Puerto Rico [4]. Once we compare the results for this case, it can help us understand how we might improve our engineering standard taking into consideration that the passing of hurricane Maria and hurricane San Felipe the Second strongly suggest that the wind loads should not be reduced.

Figure 2
A neighborhood in Puerto Rico where Several Houses Lost All Their Roofs (Source: FEMA)

CHANGES ON THE WIND PROVISIONS USED IN PUERTO RICO

As different types of landfalling hurricane impact the U.S. mainland and its territories, the design parameters for wind loads provided in the ASCE 7 standard requirements have been revised and updated throughout the years. Therefore, in this section, general observations are made about the changes on the ASCE 7 standard about the wind design requirements from 1988 through 2016 [3], [5]-[10]. This section also discusses the wind load pressures specified in the 1987 Building Regulation No. 7 [4]. In the equations that will be presented, the following nomenclature will be used:

- V = basic wind speed as provided by code, at 33 ft above ground in exposure (roughness) C.
- I = importance factor according to the building's occupancy category.
- K = factor to be used in the design as specified under the Building Regulation No. 7.
- K_z = velocity pressure exposure coefficient evaluated at height z given in the ASCE 7 standard.
- K_{zt} = topographic factor as provided by the ASCE 7 standard.
- K_d = wind directionality factor given in the ASCE 7 standard.
- Ke = ground elevation factor as provided by the ASCE 7-16 standard.
- q_z = velocity pressure evaluated at height z.
- G = gust effect factor
- C_p = external pressure coefficient to be used in determination of wind loads for buildings.
- C_q = pressure coefficient provided by the Building Regulation No. 7.
- P = design wind pressure to be used in determination of wind loads for buildings
- γ_w = wind load factor for strength design as provided by code.
- P_u = strength (ultimate) design wind pressure to be used in determination of wind loads for buildings.

Building Regulation No. 7 of Puerto Rico, 1987 Edition (Reglamento de Edificación - Reglamento de Planificación Núm. 7)

This document is an amendment to the 1968 Regulations of Puerto Rico. They are directed to the updating of the provisions of Part IV (Structural Strength) of the regulation, considering the need that the structural requirements for the design and construction of buildings and structures in Puerto Rico are in accordance with the latest technological advances and with the risk of the occurrence of earthquakes and hurricanes, as reflected by technical studies.

The provisions on minimum loads calculations were revised, taking into consideration requirements of the current Uniform Building Code at that time. This regulation was adopted by the "Administracion de Reglamentos y Permisos" (ARPE) and was approved by the Puerto Rico Planning Board.

The wind requirements are presented in Article IV-A-6.0 of the Building Regulation. The modifications related to the design requirements for wind are described as follows:

- The basic (design) wind speed provided in this regulation is 110 mph. The 110-mph wind speed was based on a statistical study by the National Oceanographic and Atmospheric Administration (NOAA).
- The design wind pressures for buildings at any height are calculated using equation (1).

$$P = C_q \, I \, K \, q \qquad (1)$$

- The basic wind pressure that varies with height, q, is given by Table IV-A-6.3a of the Regulation.
- This regulation provides designer two different types of wind load analysis: Method 1 for gable frames and lightweight structures and Method 2 for multi-story buildings with non-lightweight structural elements.
- The pressure coefficient, C_q, is given by Table IV-A-6.4a for Method 1 and is given by Table IV-A-6.5b for Method 2.

ASCE 7-88

Wind requirements are presented in Chapter 6 of the ASCE 7. The 1988 edition of the ASCE 7 had the following changes compared to the Building Regulation No. 7 of Puerto Rico:

- The basic (design) wind speed provided in this edition for the island of Puerto Rico is 95 mph 3-second gust, Exposure C, at 33 feet.
- Equation 2 is used to determine the velocity pressure that varies with height.

$$q_z = 0.00256 \, K_z \, (IV)^2 \qquad (2)$$

- The ASCE 7 standard classifies buildings and other structures according to their nature of occupancy (Category I – IV). In the Building Regulation of Puerto Rico, does not.

ASCE 7-95

Wind requirements are presented in Chapter 6 of the ASCE 7. The 1995 edition of the ASCE 7 had some changes from the 1988 edition. This change related to the design requirements for wind is described as follows:

- The first significant updates in the wind provisions since 1982 were made in ASCE 7-95 [6]. The most significant among a few important changes was that 3-second gust wind speed rather than fastest-mile wind speed, became the basis of design.
- The basic (design) wind speed provided in this edition for the island of Puerto Rico is 125 mph 3-second gust, Exposure C, at 33 feet.
- In the ASCE 7-95 standard [6], a topographic factor, K_{zt}, was included in equation (3) to determine the velocity pressure.

$$q_z = 0.00256 \, K_z \, \boldsymbol{K_{zt}} \, V^2 \, I \qquad (3)$$

- According to the commentary C6.5.5.5, the topographic factor was considered because buildings sited on the upper half of an isolated hill or escarpment may experience significantly higher wind speed than buildings situated on level ground, therefore to account for these higher wind speeds, the velocity pressure exposure coefficients are multiplied by the topographic factor.

ASCE 7-98

Wind requirements are presented in Chapter 6 of the ASCE. The 1998 edition of the ASCE 7 had some changes from the 1995 edition. These changes related to the design requirements for wind are summarized below:

- On the previous editions of the ASCE, provided designers with two different procedures to determine wind pressures on a building: the analytical procedure and wind tunnel procedure. In the 1998 edition, introduces a new procedure: the simplified procedure.
- The basic (design) wind speed provided in this edition for the island of Puerto Rico is 145 mph 3-second gust, Exposure C, at 33 feet.
- Commentary C6.5.4.4, discuss that the existing wind load factor 1.3 in the 1995 edition, includes a “wind directionality factor”, K_d, of 0.85. This factor accounts for two effects: the reduced probability of maximum winds coming from any given direction; and the reduced probability of the maximum pressure coefficients occurring for any given wind direction. The wind directionality factor was included in equation (4) to determine the velocity pressure.

$$q_z = 0.00256\, K_z\, K_{zt}\, \boldsymbol{K_d}\, V^2\, I \qquad (4)$$

- Also, according to the commentary C2.3.2 on the second paragraph, discuss that the load factor on wind load combinations (4) and (6) has been increased to 1.6 from 1.3.
- The previous value, 1.3, was based on a statistical analysis of wind forces on buildings at sites not exposed to hurricane winds. Studies have shown that, due to differences between statistical characteristics of wind forces in hurricane-prone coastal areas of the U.S., the probability of exceeding the factored wind force 1.3 is higher in hurricane-prone coastal areas than in the interior design. Two recent studies have shown that the wind load factor in hurricane-prone areas should be increased to approximately 1.5 to 1.8 (depending on site) to maintain comparable reliability.
- The definitions of Exposure C and D were changed slightly to allow the shoreline in hurricane prone regions to be classified as Exposure C, rather than Exposure D. This was based on a study of the subject by Peter J. Vickery called “On the Elimination of Exposure D along Hurricane Coastline ASCE-7” on March of 1998.

ASCE 7-02 to ASCE 7-05

Wind requirements are presented in Chapter 6 of the ASCE. The 2002 and 2005 edition of the ASCE 7, no significant changes were found from the 1998 edition [7] with the exception that in the 2002 edition [8], a distinction was made between roughness categories and exposure categories. This has enabled more precise definitions of Exposure B, C and D to be obtained in terms of the extent and types of surface roughness that are upwind of the site.

ASCE 7-10

The 2010 edition of the ASCE 7 had several changes from the 2005 edition. Some key changes related to the design requirements for wind are described as follows:

- The wind chapter was reorganized into six new chapters (26-31).
- Wind speed maps were updated and now provide wind speeds based on strength design. In the 2005 edition, 3-second gust basic wind speeds are presented in one single map.
- The most significant change in the wind speed maps from the previous version is the shift from a single map for an importance factor for buildings and other structures of 1.0 to three separate maps at much longer return periods (700 to 1,700 years), one for each category of occupancy (Category I, Category II and for Category III & IV), thus eliminating for

importance factors that vary between hurricane and non-hurricane.

- Recent research showed that the behavior of the sea surface drag coefficient at high wind speeds in hurricanes indicated that the surface roughness over the ocean does not continue to increase with increasing wind speed. Consequently, the use of Exposure D along the hurricane coastline is now required. This new exposure classification increases wind loads on buildings close to the coast.

ASCE 7-16

The 2016 edition of the ASCE 7 included further changes from the 2005 and 2010 edition. Some key changes related to the design requirements for wind are summarized below:

- Risk Category III and IV buildings have their own respective wind speed maps as opposed to one map for both Risk Categories which was the case in the 2010 edition.
- In this edition, a Ground Elevation Factor, K_e, is considered to adjust for air density above the sea level where the building is located, and is shall be determined in chapter 26.

Table 1 presents the changes in the velocity pressure equation with the different coefficients that have been incorporated throughout each edition. In the 1995 edition, the topographic factor was incorporated. Then, in the 1998 edition, the wind directionality factor was also included. In the 2010 edition, the importance factor for wind loads was eliminated as changes to the new wind hazard maps and a ground elevation factor was also included as mentioned in this section. Table 2 presents the equation used to determine the external design wind pressure as specified by the different versions of the code.

To have a better understanding of the differences between each ASCE 7 edition [3], [5]-[10], we shall proceed to calculate the ultimate external wind pressure (refer to equation 6), in accordance to the wind requirements for each edition, using the Analytical and/or Directional Procedure with the Main Wind-Force Resisting System (MWFRS) to compare the different results and see how it affects the basic wind design.

Table 1
Changes in the Velocity Pressure Equations from 1988 to 2016

ASCE Edition	Velocity Pressure Equations
1988	$q_z = 0.00256K_z(IV)^2$
1995	$q_z = 0.00256K_zK_{zt}V^2I$
1998	$q_z = 0.00256K_zK_{zt}K_dV^2I$
2002	$q_z = 0.00256K_zK_{zt}K_dV^2I$
2005	$q_z = 0.00256K_zK_{zt}K_dV^2I$
2010	$q_z = 0.00256K_zK_{zt}K_dV^2$
2016	$q_z = 0.00256K_zK_{zt}K_dK_eV^2$

Table 2
External Design Wind Pressure Equation Provided by the Codes

Code	External Design Wind Pressure Equation
ARPE 1987	$P = C_q\, I\, K\, q$
ASCE 1988 - 2010	$P = q_z\, G\, Cp$

We will calculate the ultimate external wind pressure for a Risk Category II building of 33 feet of height located in Puerto Rico for an Exposure C and an Exposure D classification. Only the windward wall, leeward wall and sidewalls of the building or structure were analyzed for this research. Since the results are equivalent in terms of findings, only the windward wall pressures are reported. The factored actions (loads) have been changing in the different editions of the codes. The following table summarizes, for each edition of the ASCE 7 code [3], [5]-[10], the wind load combination factor for strength design, for the factored load combination where the wind load in the driving force of the ultimate state considered.

Table 3
Wind load factors given in the ASCE Standard using Strength Design

Code Edition	*Wind Load Combination Factor* γ_w
1988	1.3
1995	1.3
1998	1.6
2002	1.6
2005	1.6
2010	1.0
2016	1.0

From these load combinations we will focus in the term corresponding to the wind load, as presented in equation 6.

$$P_u = \gamma_w \, q_z \, G \, C_p \qquad (6)$$

For the 1987 Building Regulation of Puerto Rico [4], we shall proceed to calculate the wind pressure (refer to equation 7), in accordance with the wind provisions under Article IV-A-6.0, using the Method 1. For the ultimate wind design calculation, we shall use the load combinations provided under the Building Code Requirements for Reinforced Concrete of 1989, ACI 318-89 [11] (Revised 1992) and of 2002, ACI 318-02 [12].

$$P_u = \gamma_w \, C_q \, I \, K \, q \qquad (7)$$

Also, since on the ASCE 7-10 [9] and ASCE 7-16 [10] wind requirements now provide updated wind speeds based on the ultimate design, we wanted to establish the corresponding equivalent wind speed (refer to equation 8) by multiplying the square root of the wind load factor with the 3-second gust wind speed provided on the maps in the ASCE 7 standard from 1988 through 2005 [3], [5]-[8] and compare them with the new wind speeds.

Comparison of Results

The calculated values for the ultimate external wind pressures for the MWFRS for a Risk Category II building of 33 feet with an Exposure C classification are shown in Table 4. Is evident that on Table 4, the ultimate external wind pressures for windward walls specified in the standard from 1998 to 2005 [3], [7]-[8], are, in general, larger wind pressures than the standard of 2010 and 2016 [9]-[10], even though the basic wind speeds are higher in these later versions of the ASCE 7. These calculations show that the 2010 and 2016 standard give the same wind pressure values, meaning that there weren't significant changes using the directional procedure for the MWFRS. Figure 3 presents a line graph that illustrates the changes in ultimate wind pressures for an Exposure C throughout the years. The line graph shows the ultimate wind pressures at its highest between 1998 and 2005 edition [3], [7]-[8], including also the Building Regulation No. 7 of Puerto Rico [4].

Table 4
Ultimate Wind Pressures at 33 ft of Height for Exposure C given in the ASCE for Windward Walls

ASCE	Wind Speed (mph)	External Pressure (psf)	Ultimate External Pressure (psf)
1988	95	28.47	37.01
1995	125	27.20	35.36
1998	145	31.11	49.78
2002	145	31.11	49.78
2005	145	31.11	49.78
2010	150	33.29	33.29
	160	37.88	37.88
	170	42.76	42.76
2016	150	33.29	33.29
	160	37.88	37.88
	170	42.76	42.76

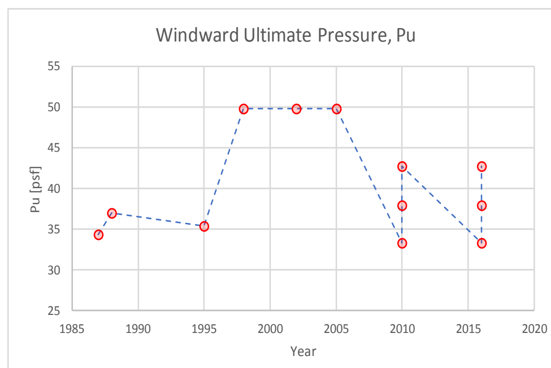

Figure 3
Ultimate Wind Pressures for Exposure C specified in the ASCE 7 and the Building Regulation Code for Windward Walls

Table 5 shows the ultimate external wind pressures for a Risk Category II building of 33 feet with an Exposure D classification. It was observed that in Table 5 shows the same pattern as in Table 4 with the exception that the external wind pressures from the 1998 through 2005 [3], [7]-[8] in hurricane prone regions, correspond to an Exposure C classification as per section 6.5.6 from chapter 6 of the ASCE 7 standard [3], [7]-[8]. In the 2010 and 2016 edition [9]-[10], a wind speed of 170 mph produces an ultimate wind pressure of 50.46 psf, that is less than 2% percent of difference between the 2005 edition [3] with a wind speed of 145 mph.

Table 5
Ultimate Wind Pressures at 33 ft of Height for Exposure D given in the ASCE for Windward Walls in Hurricane Prone Areas

ASCE	Wind Speed (mph)	External Pressure (psf)	Ultimate External Pressure (psf)
1988	95	35.61	46.30
1995	125	32.10	41.72
1998	**145**	**31.11**	**49.78**
2002	**145**	**31.11**	**49.78**
2005	**145**	**31.11**	**49.78**
2010	150	39.29	39.29
	160	44.70	44.70
	170	50.46	50.46
2016	150	39.29	39.29
	160	44.70	44.70
	170	50.46	50.46

Note: Values in bold, correspond to an Exposure C as per the ASCE 7 standard in hurricane prone areas.

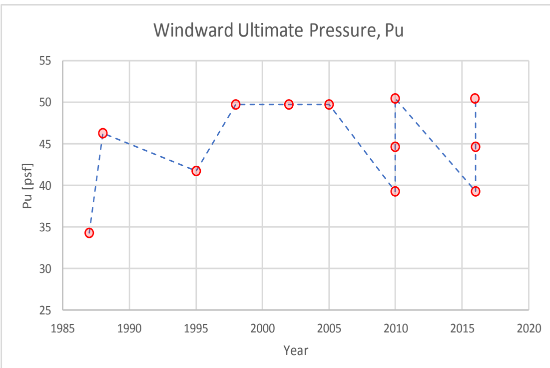

Figure 4
Ultimate Wind Pressures for Exposure D Specified in the ASCE 7 and the Building Regulation Code for Windward Walls

Figure 4 presents a graph that illustrates the changes in ultimate wind pressures for an Exposure D throughout the years, including also the Building Regulation No. 7 of Puerto Rico [4]. The graph shows an increase in the ultimate wind pressure for the 1988 edition [5]. This is because for an Exposure D classification, the values for the Velocity Pressure Exposure Coefficient, Kz, (Table 6, ASCE 7-88) and for the Gust Response Factor, G, (Table 8, ASCE 7-88) are greater than the ones specified in the 1995 edition [6]. The line graph shows the ultimate wind pressures at its highest between 1998 and 2005 edition [3], [7]-[8] and in the 2010 and 2016 edition [9]-[10] for a wind speed of 170 mph.

Table 6 shows the ultimate wind pressure for a building of 33 feet of height for windward walls using Method 1 as specified in the Building Regulation of Puerto Rico [4] and in the ACI 318-89 [11] and ACI 318-02 [12] for the wind load factors. By comparing the wind loads between each ASCE 7 edition [3], [5]-[10] and the Building Regulation of Puerto Rico [4], it was observed that by using the ACI 318-89 [11] wind load factor (1.3), the ultimate wind pressure is very similar to those that were calculated using the ASCE 7-88 [5] and ASCE 7-95 [6] for an Exposure C classification. On the other hand, by using the wind load factor specified in the ACI 318-02 [12] (1.6), the ultimate wind pressure is larger than the ASCE 7-88 [5] and the ASCE 7-95 [6]. It is interesting that even though the wind speed provided under the Building Regulation of Puerto Rico [4] is lower than the ASCE 7-95 [6], the ultimate wind pressure is larger than what is specified under the ASCE 7 standard for this case.

Table 6
Ultimate Wind Pressures at 33 ft of Height given in the Building Regulation of PR for Windward Walls

ARPE	Wind Speed (mph)	External Pressure (psf)	Ultimate External Pressure (psf)	
			ACI 318-89	ACI 318-02
1987	110	26.40	34.32	42.24

On the other hand, as per the 1987 code [4], a wind speed of 110 mph produces an ultimate wind pressure of 34.32 psf with a wind load factor as per the ACI 318-89 [11]. Then, in the 2016 edition of the ASCE [10], which has been approximately 19 years since 1987, specifies that a wind speed of 150 mph produces an ultimate wind pressure of 33.29 psf (Risk Category II, Exposure C). Between 1987 and 2016, Puerto Rico has been impacted by strong hurricanes such as hurricane Hugo and hurricane Georges and it is unreasonable that in the latest wind provision for this case, the pressures are similar between one another.

Based on these calculations and while accomplishing the objective, it was observed that the ultimate external pressures decreased in 2010 and 2016, at least for Puerto Rico. This indicates that the ASCE 7-05 [3] hurricane wind speeds are generally more conservative than the ones provided in the ASCE 7-10 [9] and ASCE 7-16 [10]. In addition, the 2011 Puerto Rico Building Code [2] (PRBC) adopted the International Building Code of 2009 (2009 IBC) which references the ASCE 7-05 [3]. Taking this into consideration, the percentage of difference for each edition was calculated using as reference the ASCE 7-05 [3] since it is the most conservative.

Table 7
Percent of Difference of Ultimate Wind Pressures for Exposure C using as Reference the ASCE 7-05 for Windward Walls

Code	Wind Speed (mph)	Difference in Ultimate Pressure (%)
1987 + ACI 318-89	110	-31.05%
1987 + ACI 318-02	110	-15.14%
1988	95	-25.65%
1995	125	-28.96%
1998	145	0%
2002	145	0%
2005	145	0%
2010	150	-33.12%
	160	-23.90%
	170	-14.09%
2016	150	-33.12%
	160	-23.90%
	170	-14.09%

Table 7 shows the percentage values for each edition, except the ASCE 7-05 [3], for Exposure C and Table 8 shows the percent values for Exposure D. It was observed that by using the wind load factor under the ACI 318-02 [12], the ultimate wind pressure decreased to 15% percent using as reference the ASCE 7-05 [3] for an Exposure C. This percent of decrease is less than the values calculated for the 1988 and 1995 editions of the ASCE 7 standard [5]-[6]. The same observation applies for Exposure D. It could be said that prior to the ASCE 7-05 [3], the wind provisions of the Building Regulation of Puerto Rico [4] were the most conservative.

In Table 7 and 8, it was observed that from the 1998 through 2005 edition [3], [7]-[8], there weren't any significant changes up until the 2010 and 2016 edition [9]-[10] for both Exposure C and Exposure D. As shown in Table 7, in the 2010 and 2016 [9]-[10], for a wind speed of 150 mph differs up to a 33% percent from the 2005 edition. But for a wind speed of 160 mph, differs up to a 23% percent and for a wind speed of 170 mph, the difference is up to a 14% percent. The most significant change shown in Table 8 is the increase of 1.37% percent in the ASCE 7-10 [9] and ASCE 7-16 [10] for a wind speed of 170 mph. This means that as the ultimate external wind pressure increases, whether it is Exposure C or Exposure D, it is approaching the ultimate external wind pressure value of the 2005 edition [3], therefore its percentage of difference increases.

Table 8
Percent of Difference of Ultimate Wind Pressures for Exposure D using as Reference the ASCE 7-05 for Windward Walls

Code	Wind Speed (mph)	Difference in Ultimate Pressure (%)
1987 + ACI 318-89	110	-31.05%
1987 + ACI 318-02	110	-15.14%
1988	95	-6.99%
1995	125	-16.18%
1998	145	0%
2002	145	0%
2005	145	0%
2010	150	-21.08%
	160	-10.20%
	170	1.37%
2016	150	-21.08%
	160	-10.20%
	170	1.37%

Since the new wind speed maps are based on ultimate design, meaning that they have a much longer mean recurrence interval than the 2005 mapped speeds, we calculated the corresponding equivalent wind speed for the 1987 through 2005, using equation 8.

$$V_e = \sqrt{\gamma_W}\ \sqrt{I}\ V \quad (8)$$

For a building located in Puerto Rico as per the ASCE 7 [3], [5]-[10], the 95 mph from 1988 is equivalent to 114 mph. On the other hand, the 110 mph from the 1987 code, is equivalent to 125 mph. In this case, is interesting on how the basic information used to determine the wind speed, they didn't consider the passing of hurricane San Felipe the Second (maximum velocity of wind at San Juan was over 150 mph). The 125 mph from 1995 is equivalent to 142 mph and the 145 mph from the 1998 to 2005 is equivalent to 183 mph. This equivalent speed is larger than the wind speed established on the single map in the 2005 edition. The 2010 and 2016 wind speeds contours for a Risk Category II building range from 150 to 170 mph which is lower than 183 mph. Figure 5 illustrates a line graph with the different equivalent velocities from 1987 through 2005 and the ultimate speed from 2010 and 2016. The line graph helps visualize the significant changes in the wind speeds between the standards and regulations throughout the years.

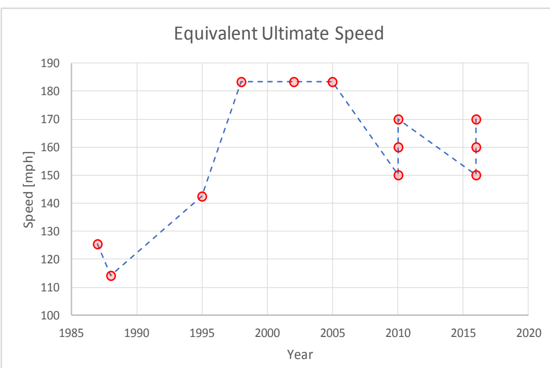

Figure 5
Equivalent Ultimate Speeds for Puerto Rico

Table 7 presents a comparison of the ultimate design wind speeds for each Risk Category (I-IV) between the calculated equivalent ultimate speed of the ASCE 7-05 [3] and the ultimate wind speeds presented in the new wind map contours given in the ASCE 7-16 [10]. It was observed that in Risk Category II, III and IV, the equivalent wind speed of the ASCE 7-05 [3] exceeds the maximum ultimate wind speed, which is the East wind contour of Puerto Rico as per the wind maps of the ASCE 7-16 [10]. The latest building codes should be, undoubtedly, re-evaluated so that the wind map contours, at least for Puerto Rico, require higher wind speeds, otherwise, these codes are in the direction of less conservatism in wind design.

Table 9
Comparison with Design Wind Speeds with ASCE 7-05 and ASCE 7-16

Category	Equivalent Wind Speed ASCE 7-05	ASCE 7-16		
		West	Center	East
I	160.94	140	150	160
II	183.41	150	160	170
III	196.69	160	170	180
IV	196.69	160	170	190

Hurricane Maria, like any other storm, had peak gusts over the design wind speed assigned for the area, and the building performance at near and/or over the design wind conditions can provide valuable lessons in determining that, in fact, further research is required to be able to update the building code provisions.

Conclusion and Recommendations

The external wind pressures specified in the ASCE [3], [5]-[10] and in the Building Regulation of Puerto Rico [4] were analyzed to determine the differences in the calculated results. The analysis included calculations of wind load pressures for only Risk Category II buildings with an Exposure C and D as per the ASCE standard.

It was observed that the changes related to the design requirements for wind in the 2010 [9] and 2016 edition [10], have resulted in a reduction in wind pressures comparing them with the 2005 edition of the ASCE 7 [3]. This would be considered worrisome because evidently that the recommendations provided under the 2010 and 2016 editions [9]-[10], although more sophisticated, will not necessarily produce safer structures.

The 3-second gust wind speed assigned to Puerto Rico (145 mph) corresponds to a Category 3 major hurricane as per the Saffir-Simpson Hurricane Wind Scale. However, the equivalent wind speed of 183 mph corresponds to a Category 5 hurricane. Due to the natural tendency of Puerto Rico to be impacted by hurricanes such as hurricane San Felipe the Second, hurricane Georges and most importantly hurricane Maria, it is important that the wind load committee revise the basic information for the development of the wind speed contours and that they should update them to require higher wind speeds. This calculation suggests that adopting a gust corresponding to a high-end Category 4 or Category 5 hurricane would be appropriate at the time of the wind load design.

The purpose of this research is to advise or assist the wind standard committee to review and revise the wind provisions and to strongly support the adaptation of strong, disaster-resistant building codes to preserve the health and safety of the public in general.

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