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Critical Load Cases Simulating Downbursts: Economical Implications for Design of Transmission Lines

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SUMMARY

An extensive research program was recently conducted at the University of Western Ontario to develop load profiles that can be used in the analysis and the design of transmission towers under downbursts. This research was motivated by many transmission line failures that have occurred in different locations around the globe during downburst events. It was also triggered by the fact that codes of practice and guidelines provide very limited information regarding the critical loading profiles associated with downbursts and acting on the towers and conductors of a transmission line system. In this research, a numerical model was developed where the downburst wind field was simulated using Computational Fluid Dynamic (CFD) modelling. The structural response was predicted using nonlinear finite element analysis that accounts for towers, insulators, conductors, ground wires and guys (in case of guyed lattice towers). One of the challenges in predicting the response of transmission towers under downburst loading is the complexity in predicting the forces acting on the tower and conductors as they are dependent on not only the magnitude of the event but also its size and location relative to the center of the tower. This complexity results from the localized nature of such events. The current research refers to an extensive parametric study that has been conducted on a number of transmission lines covering a wide spectra of transmission line systems currently in service. A transmission line of six spans has been considered in a previous study by the authors in order to capture the global response of the line. In addition, variation in the downburst location, angle of attack, and size has been considered to understand the effect of changing these parameters on the response of the transmission line system. Based on the results obtained from this parametric study, three critical load cases were identified. Because those critical load patterns are not uniform along the height of the tower, equivalent linear load profiles were then suggested and validated. In the current study, two case studies have been conducted to assess the economical implication of considering the critical downbursts load patterns.

KEYWORDS

Downburst, Microburst, Transmission line, Wind load, High Intensity Wind, Load profiles

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1 INTRODUCTION

Many studies reported that High Intensity Wind (HIW) events in the form of tornadoes and downbursts are of the main cause of transmission line failures in different countries. For instance, McCarthy and Melsness [1] reported a series of transmission tower failures under downburst in Canada. In the USA, a recent report produced by the White House [2] stated that more than 600 power outages occurred due to severe wind events. In China, Zhang [3] reported failures of more than 70 transmission towers under different HIW events. The current study focuses on evaluating the effect of downburst loading on generic transmission towers. Downburst is defined by Fujita [4] as an intensive downdraft of cold air that impinges on the ground and then transfers horizontally.

Unlike synoptic winds, the challenge of analyzing a transmission line under the effect of downbursts arises from their localized nature. This means that the response of the system to a downburst depends on the downburst diameter "D_J", the distance between the centers of the downburst and the tower "R", and the angle of attack "Θ". A schematic of the spatial parameters of the downbursts is provided in Figure 1. Moreover, the downburst intensity defined by the jet velocity "V_J" significantly affects the line system response. The oblique position of the downburst with respect to the tower of interest leads to a non-uniform and non-symmetrical distribution of the wind forces acting on the line conductors. This results in a longitudinal force developing in the line conductors due to the difference in tension forces between the two adjacent spans on the opposite sides of the tower. Current guidelines provide limited information regarding the design of transmission line systems subjected to downbursts.

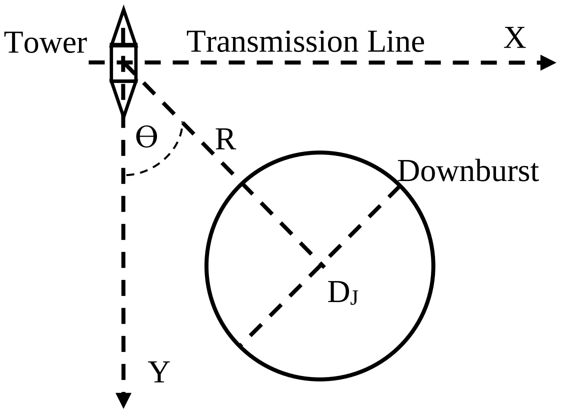


Figure 1 Downburst characteristics parameters

To predict the maximum structural response of a tower under a certain downburst velocity, large number of analyses have to be conducted by varying the downburst parameters (D_J, R and Θ). Due to their geometrical flexibility, the structural analysis of the conductors must be conducted in a nonlinear manner in order to predict the tension forces developing in the conductors and consequently the net longitudinal forces transmitted to the tower. Different members of a tower may have different downburst configurations leading to extreme internal forces in those members. The downburst wind field used in developing the critical load profiles has been previously reported by El Damatty and Elawady [5]. A brief description of this downburst wind field is provided in the next section. Descriptions of the transmission line systems, the finite element model, and the steps of analysis are then presented in sections 3 and 4. Using the critical load profiles previously proposed by El Damatty and Elawady [5], two case studies are considered, and presented in section 5, to assess the economical implications of the use of the newly developed downburst load cases. This is done by analyzing the two towers following the ASCE-74 (2010) [6] code provisions for synoptic wind, construction and maintenance loads, and broken wire case. The same towers are then re-analyzed considering the proposed critical downburst load cases using different magnitudes for the downburst event. A comparison between the internal forces developing in a number of selected members under both the downburst critical load profiles and the load cases required by ASCE-74 is reported.

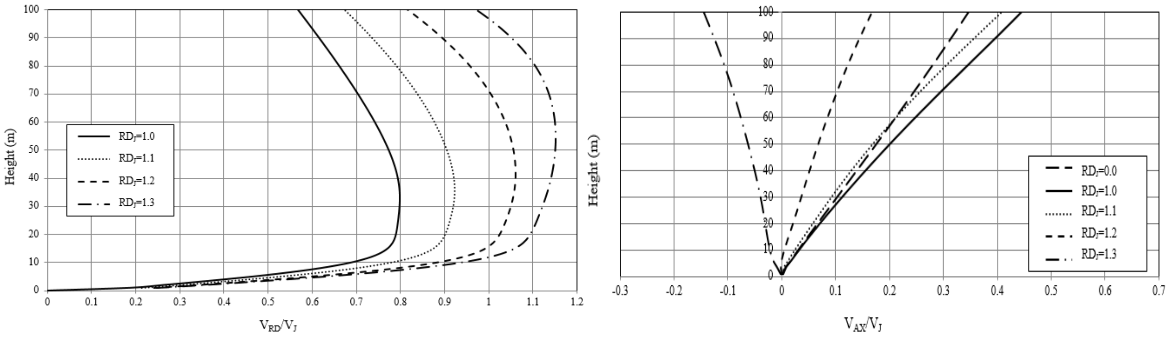
2 DOWNBURST WIND FIELD

Aboshosha et al. [7] provided a review of different numerical modelling techniques of downburst wind field that are available in the literature such as Ring Vortex Model, Impinging Jet Model, and Cooling source Model. El Damatty and Elawady [5] adopted the Computational Fluid Dynamic (CFD) model developed and validated by Hangan et al. [8] and Kim and Hangan [9], respectively. In their model, Hangan et al. [8] utilized the impinging jet model to produce a time history of the mean velocity of the radial and the vertical components of the downburst. The downburst mean wind velocity varies with time, which is why it is often referred to as the "running mean". Although the turbulent component of the wind field is important in evaluating the peak response of the structure, it was neglected in many studies due to the following reasons: 1) the period of the mean component of the downburst wind field is about 20 sec which is much higher than the periodic time of typical transmission towers which is usually less than 1 sec, 2) although the conductors are flexible, their aerodynamic damping leads to insignificant dynamic effect of downburst loads. Aboshosha and El Damatty [10] confirmed these conclusions when they studied the dynamic response of multi-span conductors under the turbulent component of both normal and downburst winds using CFD modelling. To account for the time variations of the turbulent fluctuations, turbulent velocities were scaled using a time modulation function. In their technique, the turbulence intensity of 10% was adopted as recommended by Holmes et al. [11] for the structural element design purpose. The study showed that considering the turbulent component leads to an insignificant increase in the transverse and the longitudinal forces transmitted from the conductors to the tower which was estimated by 5% and 6%, respectively. As such, no dynamic effect is considered in the current study.

The downburst wind field composed of two components; radial velocity (V_{RD}) and axial velocity (V_{AX}). Figure 2-a and Figure 2-b show the radial velocity (V_{RD}) and the axial velocity (V_{AX}) distribution along the height for different R/D_J values, respectively. In these figures, the velocities are normalized by the jet velocity. The figures show that the magnitudes of these velocities vary significantly with the change in the location and the size of the downburst. The effect of the vertical velocity component on the structural response has been excluded in this study following El Damatty and Elawady [5] recommendations due to the following facts:

- The absolute maximum value of the radial velocity component occurs when R/D_J is approximately 1.3 as shown in Figure 2-a. This peak value occurs at an elevation of approximately 50 m, which is a typical height for a high voltage transmission tower.
- The absolute maximum radial velocity is approximately equal to 1.15 V_J. This means that for a jet velocity of 50 m/sec, one would expect a maximum radial velocity slightly less than 60 m/sec.
- The maximum value for the axial velocity occurs at R/D_J= 1.0. At an elevation of 50 m, the maximum value is 0.2 V_J. Previous parametric studies such as Shehata et al. [12], Shehata and El Damatty [13], and Darwish and El Damatty [14] which considered both the radial and the axial components, have all shown that the maximum forces in the tower members occur at R/D_J values ranging between 1.2 and 1.6. For this range of R/D_J and within a height of 50 m, the maximum value of the vertical velocity will be around 0.2 V_J, which is less than 20% of the maximum radial velocity. In this critical range of R/D_J,

the axial velocity acts upward, i.e. against gravity as shown in Figure 2-b. Also, since the wind forces are proportional to the square of the velocity, the vertical forces in the critical downburst range will be significantly less than the radial forces, and thus can be neglected.



(a) (b)

Figure 2 (a) Vertical profile of the horizontal/radial outflow wind speed, D_J=500 m, ϴ=0º, (b) Vertical profile of the axial outflow wind speed, D_J=500 m, ϴ=0º (El Damatty and Elawady [5])

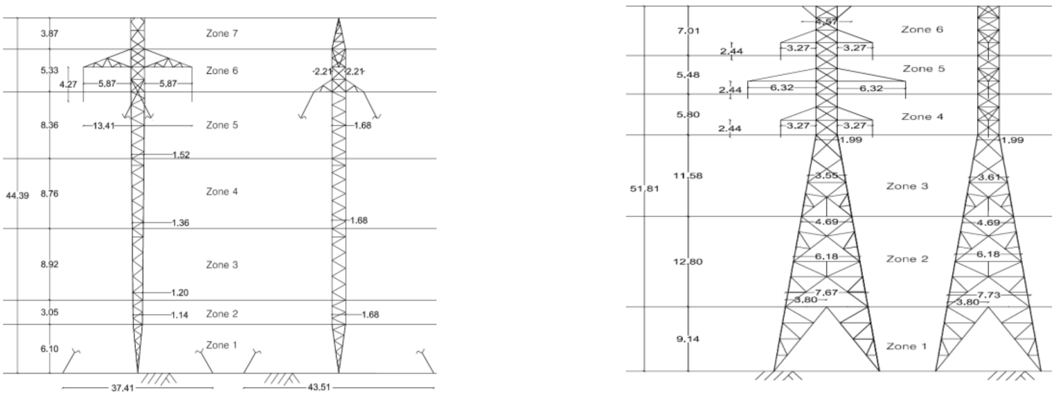
3 DESCRIPTION OF THE CONSIDERED LINE SYSTEMS

In this section, a description of the transmission line systems that have been used to evaluate the economical implication of considering the downburst load profiles is provided. Two lines have been considered in the current study; one guyed, T_1, and one self-supported, T_2, towers. The elevations and side views of the studied towers are shown in Figure 3. The height of the towers, span of the line as well as other conductors and ground wires properties are summarized in Table 1.

Table 1 Data of selected towers

Tower	T_1	T_2
Type	Guyed	Self-supported
Span (m)	480	450
Height (m)	44.39	51.81
Number of conductors	2	6
Number of ground wires	1	2
Single conductor weight (N/m)	28.97	20.14
Single conductor diameter (m)	0.04064	0.034036
Number of conductors per bundle	2	1
Ground wire weight (N/m)	3.9	3.823
Ground wire diameter (m)	0.009	0.00978
Insulator length (m)	4.27	2.44
conductor Sag (m)	20	19.5

Ground wire sag (m)	13.54	14
Modulus of Elasticity/ conductor (N/m^2)	6.23E+10	6.48E+10
Modulus of Elasticity/ground wire (N/m^2)	1.86E+11	1.05E+11
Guys diameter (m)	0.0165	N/A



(T_1) (T_2)

Figure 3 Transmission line systems used in the parametric study

4 ANALYSIS METHODOLOGY

In this section, a brief description of the downburst critical load profiles obtained previously by the authors and the adopted method of analysis is provided. El Damatty and Elawady [5] utilized the finite element model developed and validated by Shehata et al. [12] to analyze the tower while incorporating the semi-analytical technique developed and validated by Aboshosha and El Damatty [15] to analyze the conductors and the ground wires. El Damatty and Elawady [5] conducted an extensive parametric study on wide spectra of transmission line systems to investigate the critical configurations of the downburst. The analyses were conducted using the sequence shown in Figure 4.

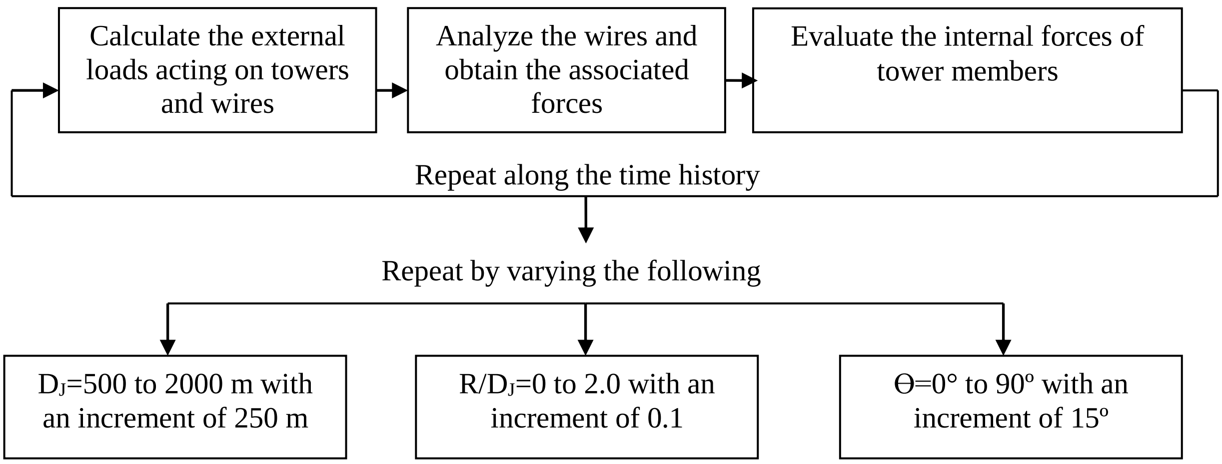


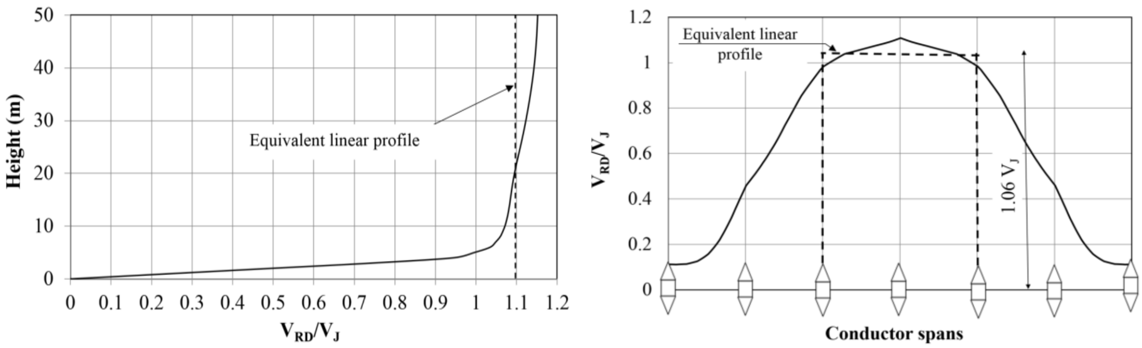
Figure 4 Flow chart summarizing the analysis steps conducted to obtain the downburst critical profiles

Based on the outcomes of that parametric study, El Damatty and Elawady [5] determined the load profiles cause the peak internal forces in tower members. These load profiles were then simplified. The description of these velocity profiles can be summarized as following:

1. Maximum transverse loads, R/D_J=1.3, ϴ=0º, D_J=500 m: this load configuration leads to a maximum velocity profile acting on the tower and the wires on the direction perpendicular to the conductor direction. The velocity profiles associated with this load case along the height of the tower as well as the spans adjacent to the tower of interest are given in Figure 5-a and Figure 5-b, respectively. The graph shows the simplified profiles proposed to account for such load case.

2. Maximum longitudinal loads, R/D_J=1.3, ϴ=90º, D_J=500 m: this load configuration leads to maximum velocity profile, shown in Figure 6, acting on the tower on the direction parallel to the conductor direction. No forces act on the conductors due to this load case. The graph shows the simplified profile proposed to account for such load case.

3. Maximum oblique loads, R/D_J=1.6, ϴ=30º, L/D_J=0.5: this case is found to cause high longitudinal force on the tower's cross arms due to the non-uniform distribution of the radial velocity along the conductors. Under this downburst configuration, two velocity components act on perpendicular sides of the tower as shown in Figure 7-a. Figure 7-b shows the transverse velocity distribution along the line spans adjacent to the tower of interest. The graph shows an equivalent linear distribution that can be used only for the calculation of the conductor's transverse force (perpendicular to the line direction). The conductor longitudinal force (in the line direction) resulting from the non-uniform profile is highly nonlinear and depends largely on the cable properties. A nonlinear analysis should be performed to estimate the longitudinal force of the conductors and the ground wires under this load configuration.



(a) (b)

Figure 5 (a) Velocity distribution along tower height, (b) Velocity distribution over six conductor spans

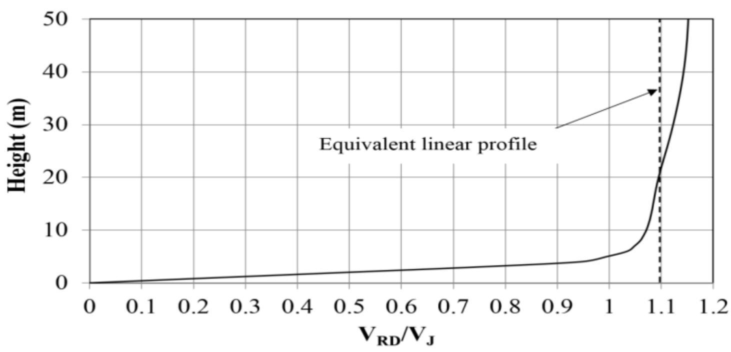
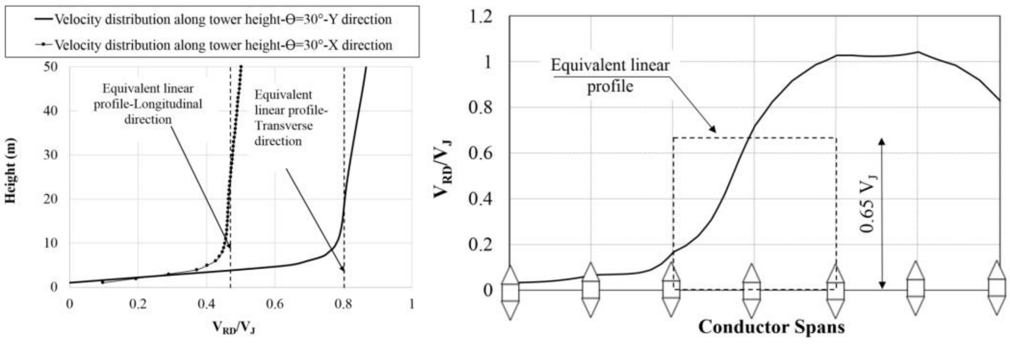


Figure 6 Velocity distribution along tower height



(a) (b)

Figure 7 (a) Velocity distribution along tower height (b) Radial velocity distribution over six conductor spans

5 Economical Implications

In the current study, the three load cases described above are used to evaluate the maximum internal forces resulting from downbursts in the members of the towers of the two considered systems. Those internal forces are compared to the members' capacity. The ratio between the acting force and the strength is evaluated for all members. When this ratio is found to exceed a value, the cross section of the member is upgraded such that this ratio becomes slightly above unity. The weight of the upgraded towers is evaluated and compared to the initial weight in order to assess the economical implication of designing the towers to resist downburst loading. A jet velocity of 50 m/sec is assumed in the study.

Table 2 shows the results for a number of selected members in each tower under this study, T_1 and T_2. The table identifies the critical downburst load case that causes the peak internal force in each member. The table shows the maximum internal forces developing in those selected members under the critical downburst load cases. The table shows the ratio between that maximum internal force resulting from the downburst loads, case of V_J equals 50 m/s, and the corresponding member capacity, $F_{DB}/F_{Capacity}$.

- ***For the guyed tower T_1:***

  ✓ The peak internal forces in the chord members of the guyed tower T_1 tends to be critical at zones 4 and 5. This is expected since the guyed tower acts as an overhanging beam, where the cantilever portion is located above the guys. As such, the maximum straining actions is expected to occur near the middle part of the beam. The analysis shows that the chord members at these zones are able to resist the downburst load. For the both guys and the conductors cross arm members, a total weight increase of 50% is needed which corresponds to a total of 42 unsafe members out of 48 member in that zone. By considering all the tower members, the analysis shows that if the tower is designed to resist the proposed downburst load cases, an upgrade is needed for a number of members which results in a **3.5%** increase in the total weight of the tower.

- ***For the self-supported tower T_2***:

  ✓ The peak internal forces in the chord members of the self-supported tower T_2 tends to be critical at zones 1, 2, and 3. This is expected since the self-supported tower acts as a free cantilever with a maximum straining actions happening at the fixation zone. The analysis shows that in order for these chords to resist the downburst load, an increase in the weight of those members of approximately 44% is needed which corresponds to a number of 31 unsafe member out of 60 member. For the cross arm chord members, a total increase in the failed members weight of 35% is needed which corresponds to a total of four unsafe members out of 12 members in this zone. By considering all the tower members, the analysis shows that if the tower is designed to resist the proposed downburst load cases, an upgrade is needed for a number of members which results in **17.5%** increase in the total weight of the tower.

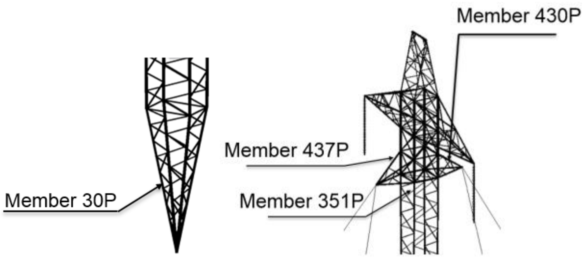


Figure 8 Guyed tower T_1 selected members

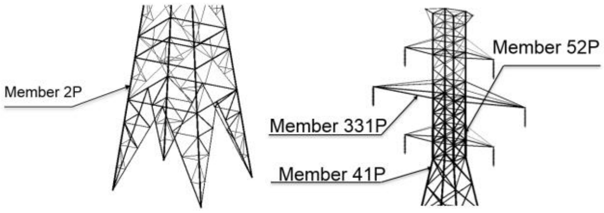


Figure 9 Self-supported tower T_2 selected members

Table 2 Two case studies results

Member	Type	Downburst linear profiles			$F_{DB}/F_{Capacity}$
		Critical Load Case	Axial Force (kN)		
			V_J =70 m/s	V_J=50 m/s	%
Guyed tower T_1					
30P	Chord	2	-63	-30	16.3
351P	Chord	1	-192.2	-98	35
430P	Guys Cross arm diagonal	2	-105	-53	200
437P	Guys Cross arm-diagonal	3	-81	-42	227
Self-supported tower T_2					
2P	Chord	1	-1334	-686	295
41P	Chord	3	-1240	-632	272
52P	Chord	1	-790	-403	60
331P	Cross arm chord	3	-143	-72	138

6 CONCLUSION

Two case studies are conducted to evaluate the economical implications of designing transmission towers to resist the previously proposed critical downburst load cases. The study first provided a brief description of the downburst wind field and then introduced those critical load cases. The study considered one guyed and one self-supported transmission line systems. The two lines are modelled using an in-house finite element model and are then analyzed under the downburst load cases. A comparison between the maximum internal forces developing in the tower members using the downburst critical load cases to the members corresponding capacity is conducted. An upgrade for those members that are found to be unsafe under the downburst load cases is considered. The increase in the weight of the towers resulting from redesigning those upgraded members is found to be equal 3.5% and 17.5% for the guyed and the self-supported towers, respectively.

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