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Load Cases Simulating Tornadoes – Economic Implications for Transmission Line Structures Design

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SUMMARY

Tornadoes are considered one of the main reasons of transmission line structures failures in various locations around the globe. Despite this fact, research studies related to this topic have been quite rare. In addition, the current codes of practice for designing transmission line structures do not include detailed provisions that account for tornado loading and the design wind loads are based mainly on large scale storms with conventional boundary layer wind profile. In the past few years, researchers at Western University, Canada, have been investigating this subject thoroughly. The research was conducted numerically and experimentally, characterizing the tornado wind field and identifying the associated structural behaviour. The research started by developing and validating tornado wind fields corresponding to various tornado scales and various terrain conditions. A numerical model that couples these tornado fields with nonlinear finite element modelling of the tower components and the conductors is then developed. Due to the localized nature of tornadoes, the forces acting on a transmission line depend on the location of the tornado, thus, various members of a tower can have different tornado locations leading to maximum internal forces in those members. Accordingly, a comprehensive parametric study that involves varying the tornado location relative to the towers needs to be conducted to determine the critical effect of tornadoes on a transmission on a transmission line system. By considering various transmission line systems, covering various tower configurations, tower heights, line spans, conductors and ground wires configurations, generic critical load cases have been identified for both the towers and the conductors. Those load cases have been proposed to the ASCE manual of practice no. 74 Committee, which is in charge of the development of guidelines for electrical transmission line structures loading. A description of the load cases and their method of implementation is provided in this paper. The load cases are confined to F2 tornadoes since the majority of the experienced tornadoes are shown to be either equal to or less than this level and it is also unfeasible to design towers to resist higher levels of tornadoes. In this paper, an economical study is conducted to assess the consequence of including tornado loading in the design of transmission lines. Two towers are designed using the conventional load cases identified in the design codes. These towers are redesigned under the set of critical load cases mentioned above simulating F2-tornado loading. The variation in the weight of the towers, which directly reflects into variation in cost, is the calculated for various towers. The study assists in assessing the economic implication of designing transmission towers to resist tornadoes.

KEYWORDS
Transmission Lines, Tornadoes, Wind Load Guidelines, Design

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1. INTRODUCTION

Electrical energy plays a vital role in many aspects of daily life. Transmission lines are responsible of carrying electricity from the source of production to the end users. Failure of transmission lines can have negative consequences from both social and economic perspective. Thus, it is important to understand how failures occur, and how to prevent them. McCarthy and Melsness [1] reported that High Intensity wind (HIW) events, such as downbursts and tornadoes, are responsible for more than 80% of all weather-related transmission line failures worldwide. This is due to the extended distance that these systems occupy, which makes the probability of having one of the towers of an extended line within the path of a tornado to be relatively high. Once one tower fails due to a tornado, progressive failure of adjacent towers can occur because of the longitudinal force that results from the de-attachment of the conductors. Another measure for the percentage of failures due to HIW events can be concluded from the questionnaire circulated by CIGRÉ [2] on transmission line failures in different countries. The responses indicated that 65% of weather-related failures were caused by HIW events. Ishac and White [3] reported that tornadoes are the main reason of most of transmission line failures in Southwestern Ontario, Canada. In addition, this region experiences about 2 tornadoes per 10,000 km^2 per year and 92% of those tornadoes are F2 or less on the Fujita scale. This makes transmission lines / towers among the most critical structures to HIW loading.

A large research program started more than a decade ago at Western University, Canada, that focused on the effect of HIW on electrical transmission line structures. The research was triggered by multiple failures in transmission towers in North America, Australia and in other regions worldwide due to HIW events. Another reason behind the initiation of this large research program at Western University is the lack of information about HIW loads in almost all design guidelines such as ASCE (2010), NERC (2007), IEC (2003) and BSI (1986). Wind loads specified in all those guidelines are based on the atmospheric conventional boundary layer large-scale type of events. The research was conducted numerically and experimentally, characterizing the tornado wind field and identifying the associated structural behaviour. The research started by developing and validating tornado wind fields corresponding to various tornado scales by Hangan and Kim and Hamada *et al.* [4,5]. A numerical model that couples these tornado fields with nonlinear finite element modeling of the tower components and the conductors was then developed and validated by Hamada *et al*., Hamada and El Damatty and Altalmas *et al*. [5,6,7]

Fujita [8] defined the tornado as a highly convergent swirling wind affecting a relative narrow path. Tornadoes can be classified by the damage-based Fujita scale starting with the smallest scale as F0 and reaching up to a scale of F5. As stated by Morrison *et al.* [9], the Fujita scale is an indicator of common or average levels of damage at a particular range of wind speeds. Field measurements are probably the best means for understanding the characterization of the tornadoes wind field. However, because of the tornadoes' localized nature and severity, such measurements are quite difficult to be obtained and are consequently rare. Thus, laboratory simulations can be used as an alternative. Tornado Vortex Chambers (TVC), simulating tornadoes as vortices, were used by many investigators as they provide a good simulation for the flow characteristic inside the tornado. However, the results can be sensitive to the type of the applied boundary conditions particularly at the near ground region [10,11]. With the advancement of computational fluid dynamic (CFD) tools, numerical modeling can be a good approach for the characterization of the wind field, especially if combined with field measurements validation.

Despite the importance of this subject, studies related to the structure performance of transmission line structures under tornadoes are few. Many challenges appear when studying the behaviour of the transmission line system under tornadoes. As shown in Figure 2 to 4, the wind velocities and loads depend mainly on the location of the tornado relative to the line and also these velocity profiles are different than the conventional boundary layer wind profile. In addition, the velocity profile along the conductor length can be highly non-uniform and varies from a conductor span to another. Thus, predicting the internal forces in the tower members belonging to a certain line requires conducting a large number of analyses by moving the tornado in space as shown in Figure 1.

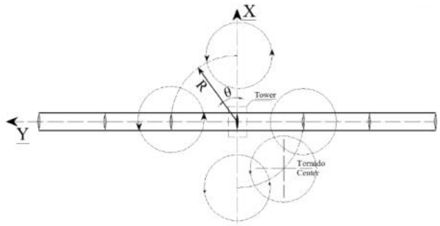

Figure 1. Tornado configurations *R* and *θ*

Many investigators conducted valuable research studying the behaviour of transmission line structures under conventional boundary layer wind loads. Few attempts have been made in the literature to investigate the behaviour of transmission line systems under HIW events. In 2001, Savory *et al.* [12] investigated the failure of a self-supported lattice tower, without considering the conductors, under modelled tornado and microburst wind profiles. In this tornado model, only the horizontal wind profile of F3 tornadoes was considered. Hamada *et al.* [5] was able to relate the F2 tornado wind field to the CFD tornado scale model that was developed by Kim and Hangan [4]. A comparison was done between the behaviour of the guyed transmission line system under the F2 and F4 tornado wind fields and that under the effect of the ASCE manual of practice no. 74 proposed conventional boundary layer wind field. The study showed significant differences between the effects of both types of winds on the structure. Hamada and El Damatty [6] investigated the sensitivity of the tower members' internal forces to the location of the tornado relative to the transmission line system. In addition, the dynamic effect of the tornado due to the translation motion was also assessed. This study revealed that the dynamic effect of the tornado translation had a minor effect due to the high aerodynamic damping of the conductors, and the significant difference between the loading period (minimum of 13 sec) and the towers period (about T = 0.5 sec). Altalmas *et al.* [7] and El Damatty and Hamada [13] assessed the transmission lines' failure mechanisms under critical tornado configurations and also predicted the maximum tornado velocity that various lines can withstand. Hamada and El Damatty [13] assessed the behaviour of two guyed transmission line structures under F2 tornado wind field, boundary layer wind, electrical companies' recommended wind field, and CIGRE` (2009) recommended tornado loading cases. Hamada and El Damatty [14] studied the failure of two guyed transmission line structures under F2 tornado wind field. The study demonstrated the effect of the guys position on the failure mode, either bending or shear failures. In addition, it showed the effect of the conductors' number and cross arms configurations on the overall behaviour of the latticed transmission guyed tower.

Due to the complexity of the tornado wind field and its localized nature, a comprehensive parametric study that involves varying the tornado location relative to the towers needs to be conducted to determine the critical effect of tornadoes on a transmission on a transmission line system. By considering various transmission line systems, covering various tower configurations, tower heights, line spans, conductors and ground wires configurations, generic critical load cases have been identified for both the towers and the conductors by El Damatty *et al.* [15]. Those load cases have been proposed to the ASCE manual of practice no. 74 Committee [16]. The objective of this study is to assess through case studies the economic implications of applying the newly developed tornado load cases in the design of transmission towers. The tornado wind field, the considered transmission line systems, the numerical model and the proposed tornado load cases are briefly described in this paper. The results of the study conducted to assess the economic implications for applying the tornado load cases in the design are then presented, followed by the conclusions withdrawn from the study.

2. DESCRIPTION OF F2 TORNADO WIND FIELD

As mentioned above, Hangan and Kim [4] developed and validated a CFD simulation for tornado wind fields corresponding to various tornado scales with the 1998 Spencer South Dakota F4 tornado and the 1999 Mulhall F4 tornado. The current study is based on this wind field. The tornado wind field has three velocity components; a tangential, a radial, and a vertical component. The vertical profiles of the three velocity components for an F2 tornado at various distances (*r*) measured from the tornado center are shown in Figure 2 to 4.

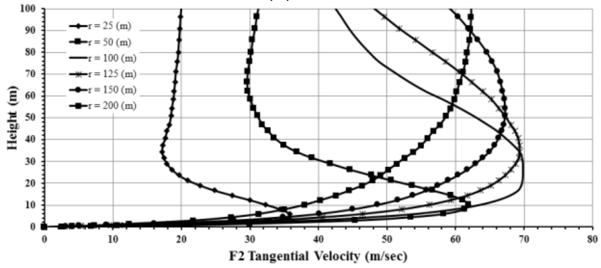

Figure 2. Tangential velocity vertical profile at different distances (*r*) from the center of the F2 tornado

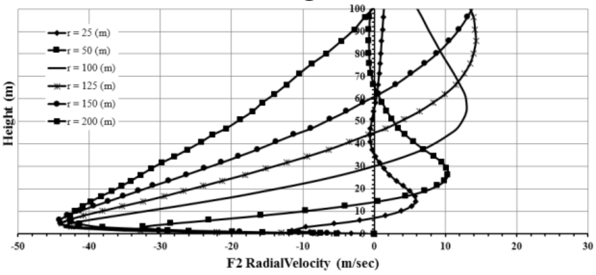

Figure 3. Radial velocity vertical profile at different distances (*r*) from the center of the F2 tornado

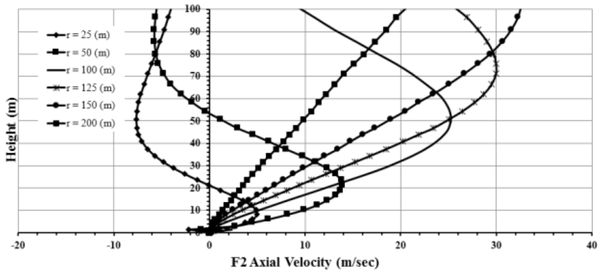

Figure 4. Axial velocity vertical profile at different distances (*r*) from the center of the F2 tornado

The significant variation of the three velocity components, in term of profiles and magnitude, along "*r*" is very noticeable in the three plots. For the tangential component, it's found that as the distance *r* increases, the peak value moves up relative to the ground level and arrives its maximum value at *r* = 100 m and *r* = 125 m. at *r* = 200 m, the tangential component vertical profile approaches the boundary layer wind profile. On the other hand, regardless of the distance *r*, the radial component peak velocities appear at the same height with almost similar value. The positive value in Figure 3 indicates an outward velocity. The magnitude of the axial velocities is less than both the tangential and radial components. Within a height of 50 m measured from ground level, which is a typical maximum height of transmission towers, the peak axial velocity (upward) occurs at *r* = 100 m and *r* = 125 m.

3. TRANSMISSION LINE SYSTEMS

Two lattice transmission line systems are used in this study; one guyed lattice transmission line system and one self-supported lattice transmission line system. As shown in Figure 5, the guyed tower height is 46.57 m and is supported by four guys attached to the tower's bridge. Three conductor bundles are connected to the cross-arms and the bridge using a 4.72 m suspension and V-suspension insulators. Two ground-wires are attached to the top of the tower. The transmission lines have a span of 460 m and a sag of 16 m. The self-supported tower height is 51.8 m and has six conductors' bundles connected to the line's cross-arms using a 2.4 m insulator strings. Two ground-wires are attached to the top of the tower. The transmission line system span is 450 m. The conductors and ground-wires sags are 20 and 12 m, respectively.

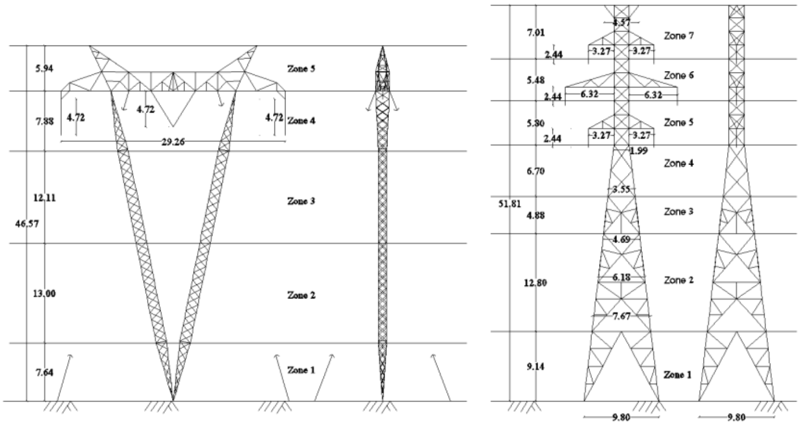

Figure 5. Towers schematic layout

4. NUMERICAL MODEL

The two transmission line systems are modeled using nonlinear three-dimensional finite element models using the commercial software SAP 2000 (CSI Inc. 2010). The tower members are modeled using two-nodded three-dimensional frame element. The chord members are assumed to be rigidly connected due to the use of multi bolted connection between members. The lines and tower guys are modeled using two nodded three dimensional nonlinear cable elements taking into account the tension stiffening. The geometric nonlinearities are taken into consideration in the modeling of all components of the transmission line systems. Hamada and El Damatty and El Damatty *et al.* [14,15] concluded that the numerical simulation of a transmission line system under tornadoes should consist of the tower of interest and two towers from each side.. As a result, the numerical model of the transmission line system includes 5 towers with 6 bays of conductors and ground-wires, as shown in Figure 6. More details regarding the finite element modeling of the transmission lines are provided by Hamada *et al.* and Hamada and El Damatty [5,6].

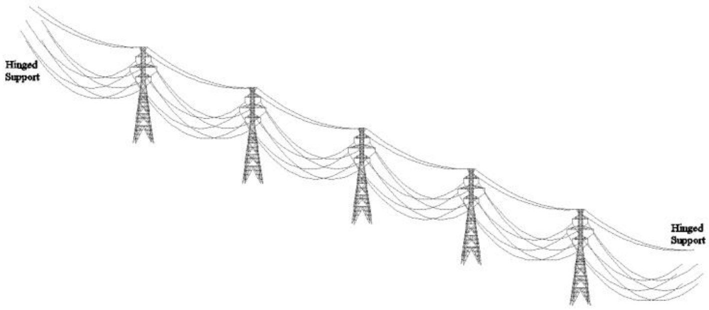

Figure 6. Schematic layout of the transmission line system numerical model [15]

5. PROPOSED LOAD CASES AND APPLICATION

El Damatty *et al.* [15] developed two simplified load cases that can be applied by practitioners in designing transmission line systems under F2 tornado wind loads. Those load cases are conservative to envelop the peak internal forces induced in various members of transmission towers when parametric studies were conducted. Each of these load cases has two perpendicular vertical velocity profiles to be applied along the tower's height, as shown in Figure 7. This is in addition to a uniform horizontal wind profile to be applied in the transverse direction for both the conductors and the ground wires.

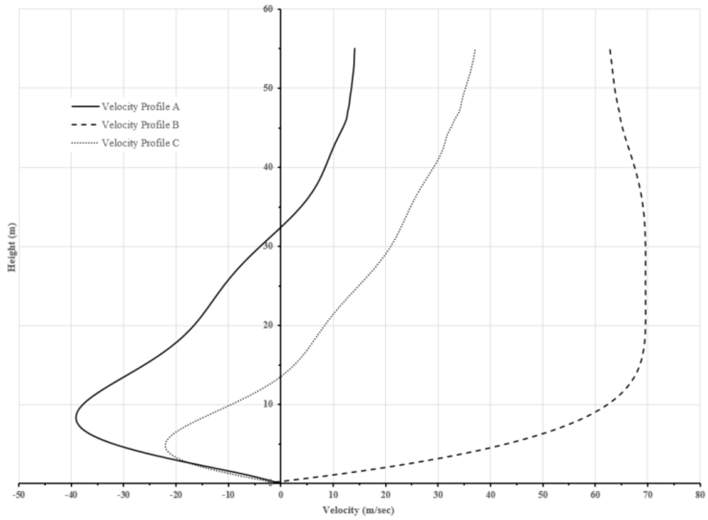

Figure 7. Vertical velocity profiles A, B and C [15]

Those profiles can be used to evaluate the velocity at each nodal point and then the forces can be evaluated using the procedures specified in the design code or the manual of practice employed by the user; e.g. Eq. 1 provided by ASCE 2010 MOP # 74.

$$F_w = \frac{1}{2}\rho_a K_z K_{zt}(V_i)^2 G C_f A_i \tag{1}$$

where F_w is the wind force at the transverse direction (N), ρ_a is the air density = 1.225 (kg/m^3); K_z is the velocity pressure exposure coefficient; K_{zt} is the topographic factor; V_i is the tornado velocity component in the transverse direction (m/s), A_i is the projected area of all the elements connected to the considered node and perpendicular to the transverse direction, G is the gust response factor, and C_f is the drag force coefficient. The values of G, K_{zt}, and K_z, are assumed equal to 1, as recommended by the ASCE 2010 MOP # 74. A value of C_f = 1 is assumed for the conductor as specified in the ASCE 2010 MOP # 74. As the F2 tornado path width varies from 110 m to 250 m, which are typically less than the conductor span, the uniform wind force on the conductors and ground wires are reduced using the span reduction factor (*SRF*) proposed by Behncke and Eric Ho [17]. The tornado *SRF* is calculated using Eq. (2):

$$SRF = W_G(1 - 0.25W_G / L) / L \tag{2}$$

Where L is the average span length and W_G is the tornado gust width. The tornado gust width (W_G) was assumed to equal to 150 m.

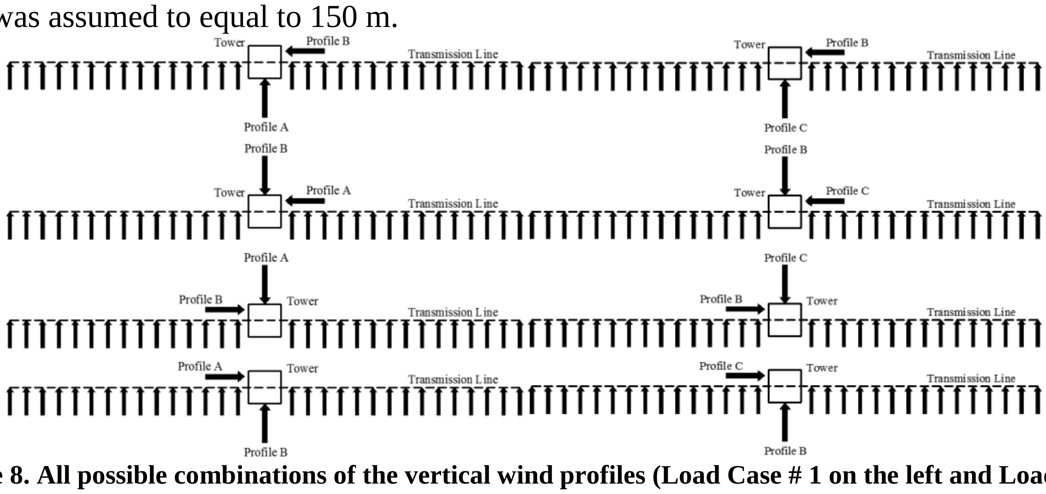

Figure 8. All possible combinations of the vertical wind profiles (Load Case # 1 on the left and Load Case # 2 on the right) [15]

For the first load case, wind profile A is applied on one face of the tower of interest combined with the wind profile B acting on the perpendicular face of the tower. On the other hand, the wind profile C is applied on one face of the tower and profile B is applied on the perpendicular face for the second load case. The uniform velocity wind profile, with speed of 72 m/sec, is applied on the transmission lines with a *SRF* incorporated. For each transmission system, the following load combinations must be considered as shown in Figure 8.

6. ECONOMIC IMPLICATIONS

In this study, the economic implications of designing the two considered line systems to resist the proposed F2 tornado load cases are assessed. Both lattice transmission line systems are analyzed under the above described F2 tornado load cases. The peak internal forces that result from the tornado load cases are evaluated for the chord, cross arm and diagonal members. Those internal forces are then compared with the members' capacities. The members that turn to be inadequate are then increased such that their capacities become just sufficient to resist the tornado loading. The final weight of the towers upgraded to resist the F2-tornado loading is determined and compared with the original weight of the towers. The results for some selected members at different zones of the guyed and self-supported towers are provided in Tables 1 and 2, respectively. Since the design of the members is governed by compression, the peak compression forces resulting from the tornado analysis as well as the members' compressive capacity are provided. The ratios between the tornado internal forces and the members' capacity are calculated and are also provided in the tables.

Table 1. Comparison between the axial internal forces due to F2 tornado wind loading and the guyed tower members' capacity

Zone	Member		Axial Internal Forces	Member Capacity	Ratio
	No.	Type	Comp. (kN)	Comp. (kN)	Comp. (%)
Zone 1	1306	Chord	-241	-253	95
	1397	Chord	-326	-253	128
		Diagonal	-16	-28	57
Zone 2	1702	Chord	-343	-257	133
	1846	Chord	-400	-256	156
		Diagonal	-20	-28	71
Zone 3	1467	Chord	-450	-277	162
	1483	Chord	-408	-277	147
		Diagonal	-18	-45	40
Zone 4	1514	Chord	-302	-253	119
	1692	Chord	-183	-239	77
		Diagonal	-39	-45	86
Zone 5	1217	Cross Arm	-160	-326	49
	1078	Cross Arm	-7	-14	49

Table 1 shows that the internal forces in the chord members of the guyed transmission tower highly exceed the capacity of these members at zones 2 and 3. Treating the guyed tower as an over-hanging beam, the maximum equivalent bending moment occurs in those zones. It is found that 60% of the guyed tower chord members (182 out of 303 members) and 3% of the cross arm members (4 out of 133 members) need to be redesigned and upgraded in order to resist the F2 tornado loading. The percentage of increase in the weight of the entire tower is found to be 23%.

For the self-supported tower, as shown in Table 2 the internal forces in the tower's chord members exceed their capacity near the ground at zones 1, 2 and 3. This is a result of the cantilever behaviour of the self-supported tower as the maximum straining actions happen near the ground. It is found that 53% of the chord members (53 members out of 100 members) and 10% of the cross arms needed an upgrade. The upgrade of those members results in 18% increase in the total weight of the tower.

Table 2. Comparison between the axial internal forces due to F2 tornado wind loading and the self-supported tower members' capacity

Zone	Member		Axial Internal Forces	Member Capacity	Ratio
	No.	Type	Comp. (kN)	Comp. (kN)	Comp. (%)
Zone 1	432	Chord	-415	-505	82
	439	Chord	-860	-505	170
	494	Diagonal	-103	-121	85
Zone 2	6	Chord	-749	-526	142
	16	Chord	-327	-526	62
	550	Diagonal	-87	-181	48
Zone 3	28	Chord	-315	-585	53
	34	Chord	-662	-585	113
	95	Diagonal	-7	-12	58
Zone 4	38	Chord	-725	-580	125
	44	Chord	-213	-580	54
	122	Diagonal	-112	-165	68
Zone 5	45	Chord	-314	-629	49
	52	Chord	-249	-673	37
	129	Diagonal	-97	-165	58
	332	Cross Arm	-342	-322	106
Zone 6	57	Chord	-173	-402	43
	62	Chord	-227	-402	56
	277	Diagonal	-76	-132	57
	2825	Cross Arm	-121	-25	20
Zone 7	72	Chord	-85	-181	46
	80	Chord	-25	-155	16
	282	Diagonal	-62	-132	47
	3058	Cross Arm	-88	-120	73

7. CONCLUSION

This study is triggered by the fact that tornadoes are considered one of the main causes of failure of transmission line structures. This study assesses the economic implications of designing transmission lines to resist F2-tornado loading. The study benefits from the recent development of load cases simulating the critical effect of tornadoes on transmission line structures. Those load cases are introduced in the paper and are then applied on two transmission line systems; one with guyed towers and the second with self-supported towers. The two lines are modelled using the finite element method and are then analyzed under the tornado load cases. Peak tornado internal forces are evaluated for all members and are compared to the compression capacity of those members. Members subjected to tornado internal forces that are found to exceed their capacities are redesigned and upgraded such that their capacities are almost equal to the acting tornado forces. The increase in the weight of the towers resulting from the upgrade in the member cross sections is found to be equal 23% for the guyed towers and 18% for the self-supported towers.

8. ACKNOWLEDGEMENT

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