Failure analysis of transmission line tower subjected to combined wind and dust loads

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Towers play a vital role in the transmission line (TL) system. The main objective of the present study is to analyse the failure of towers subjected to dust storms. This study, analyses the failure of a 765 kV single-circuit delta-type horizontal configuration tower in the river delta region near Agra. TL towers are designed based on IS 802 Part 1/Sec 1 and 2 standards. Dust particles of soil may be lighter individually, but have definite density. The wind carrying dust particles may increase the wind pressure on the tower line system. The increased wind pressure significantly affects the sag and tension of ground wire and conductor and results in additional loads on the tower, thus causing failure. It also increases wind load on the tower body and insulator string. There is literature related to numerical and wind tunnel studies on the combined effect of wind and rain loads, but no information is available on the wind and dust loads at present. The density variation method is used in the present study for calculation of additional wind pressure due to dust particles during storms. A relation between density of air mix, volume fraction of dust and density of dust particles is considered. Using FEM software, the tower is analysed for existing design loads and verified for its strength adequacy. The tower stability is studied by analysing for additional loads considering the presence of dust particles in the wind for three different volume fractions of 0.01%/m^3, 0.02%/m^3 and 0.03%/m^3. The wind pressure increases by about 10% for an increase of every 0.01% of dust particles in the wind. The tension in the conductor and ground wire increases by 8%. The existing tower design is inadequate to withstand the additional forces from wind storms associated even with a small fraction of dust particles and may be the reason for the failure of towers in northern India during a particular period of the year.

Keywords: Dust storms, failure analysis, power supply, transmission line towers.

TRANSMISSION LINE (TL) towers play a vital role in the power transmission system. Full-scale testing of TL towers is mandatory throughout the world. The tower design depends on ultimate stresses and the loads are based on the reliability/return period concept. A dust storm is a meteorological phenomenon common in arid and semi-arid regions. Westerly winds typically bring loose sand and soil particles from the Arabian Peninsula or Thar Desert in northwestern India to the Indo-Gangetic Plains (IGP) from March to May, the pre-monsoon season. Dust storms commonly occur in the IGP stretching from the western state of Rajasthan to the eastern state of Uttar Pradesh. The dust storm which occurred in 2018 was more devastating than the previous one as the weather system carried more dust and resulted in the collapse of 19 towers in the 765 kV line and 11 towers in the 400 and 220 kV lines across the three northern states. In 2014, around 30 TL towers failed in north India during a dust storm. The failure rate was much higher (55–70%) in suspension-type than in tension-type towers; this may be due to cascading effect of the failure of the suspension tower and secondary failure of adjacent suspension towers due to the pulling force of conductors developed due to failure. In most cases, the utilities point to the high-intensity wind as the cause for tower failures, but not able to substantiate due to non-availability of exact wind data at failure location. It indicates the fragility of the grid infrastructure against dust storms. The combined effect of wind and dust loads on TL towers has not been studied either numerically or in a wind tunnel. Additional wind pressure due to the presence of dust particles is predicted by modifying the air density.

The density of air combined with dust particles is equal to air density plus volume fraction of dust particles multiplied by its density. Geographical data indicate sandy loam deposits are dominant in the IGP with a density of 1460 kg/m^3. The wind associated with the dust particles increases the wind pressure and thereby load on the tower. Figure 1 shows the recent failure of a 765 kV TL tower during a dust storm. In the present study, a 765 kV tower has been considered in detail for the additional wind loads due to wind carrying the dust particles. The member forces and the capacity predicted using Indian design standards have been compared. The increase in member forces and its effect on the stability of the tower are studied.

Literature review

Fu and Li[1] presented a methodology for conductor load calculation due to combined wind and rain, and concluded

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Figure 1. Collapsed and intact 765 kV, single-circuit, delta-type transmission tower.

that the effect of rain load is significant. Drag coefficient accounting for the combined effect of wind and rain loads was derived based on wind tunnel test results[2]. The failure mechanism of a 110 kV TL tower that failed during a super typhoon in China due to wind and rain loads was studied by An *et al.*[3]. Dynamic analysis on four-span TL system subjected to typhoon wind and rain loads was performed, and it was concluded that axial force increases up to 12%. Zhang and Xie[4] studied a 220 kV river-crossing suspension tower that had failed under strong wind loads by performing static nonlinear and dynamic analysis to predict the most vulnerable panels of the tower, and emphasized the importance of dynamic analysis. The nonlinear static pushover analysis technique predicts the actual load factor and plastic hinge formation on towers subjected to wind load[5]. Fu *et al.*[6] studied TL towers under the action of extreme wind load by conducting the full-scale test on a 230 kV suspension tower and developed a uniform imperfection mode method to estimate strength capacity.

The wind with rainfall causes collapse at a lower basic wind speed than pure wind condition. The rainfall effect becomes increasingly significant with increasing number of bundle conductors[7]. Rain load has a substantial effect on the dynamic response of transmission tower-line systems. A raindrop impinging process exhibits both positive and negative forces and the peak values are of the same order of magnitude[8]. Tian *et al.*[9] conducted a wind-induced collapse analysis of long-span TL system considering the member buckling effect. The interaction between bending moment and shear deformation was found to be critical to the collapse of a tower[9].

Dynamic analyses on a TL system with three towers and four spans after an insulator breakage under ice load showed that a higher ice load can lead to more severe vibration. Insulator breakage in higher span lengths can result in the cascading collapse of the TL system[10]. Tian *et al.*[11] proposed a procedure for simulating the failure process based on the full-scale tests on TL towers subjected to various loading patterns. The multi-scale finite element (FE) method using shell elements to model the potential local failure areas and beam elements to model other parts can effectively simulate stress concentration around the bolt connections and cross-section plastic collapse of the critical structural members[12]. Nonlinear static pushover analysis on existing TL towers under wind loading indicated that the collapse mechanism differing from the intended goals of the code for developing a significant inelastic response in a large number of elements instead showed a local concentration of the damage with non-uniform distribution of yielding within the height[13].

Fu *et al.*[14] proposed a methodology based on the equivalent basic wind speed concept for fragility analysis of towers subjected to wind and rain load. They concluded that the rain load contributes significantly to tower collapse[14]. The capacity curve for a tower within the TL can be determined adequately by conducting a nonlinear static pushover analysis on a single tower[15]. Studies on progressive collapse vulnerability of a 400 kV tower in a TL system showed that it may resist the progressive collapse due to possible alternative load paths[16].

Strong wind and rain load significantly affect the reliability of the transmission line system[17]. The influence of rain load cannot be ignored on the TL tower during strong rainstorm[18]. Xie and Sun[19] conducted an experimental study on two pairs of sub-assemblages consisting of single and double panels, similar to the 500 kV tower damaged during an ice disaster with and without diaphragm bracing. The diaphragm bracing increased the ultimate strength by 18.3% and 17.6% for the single- and double-panel tower sub-assemblages respectively[19].

The basic wind speed depends on peak gust velocity averaged over a short time interval of about 3 sec (ref. 20).

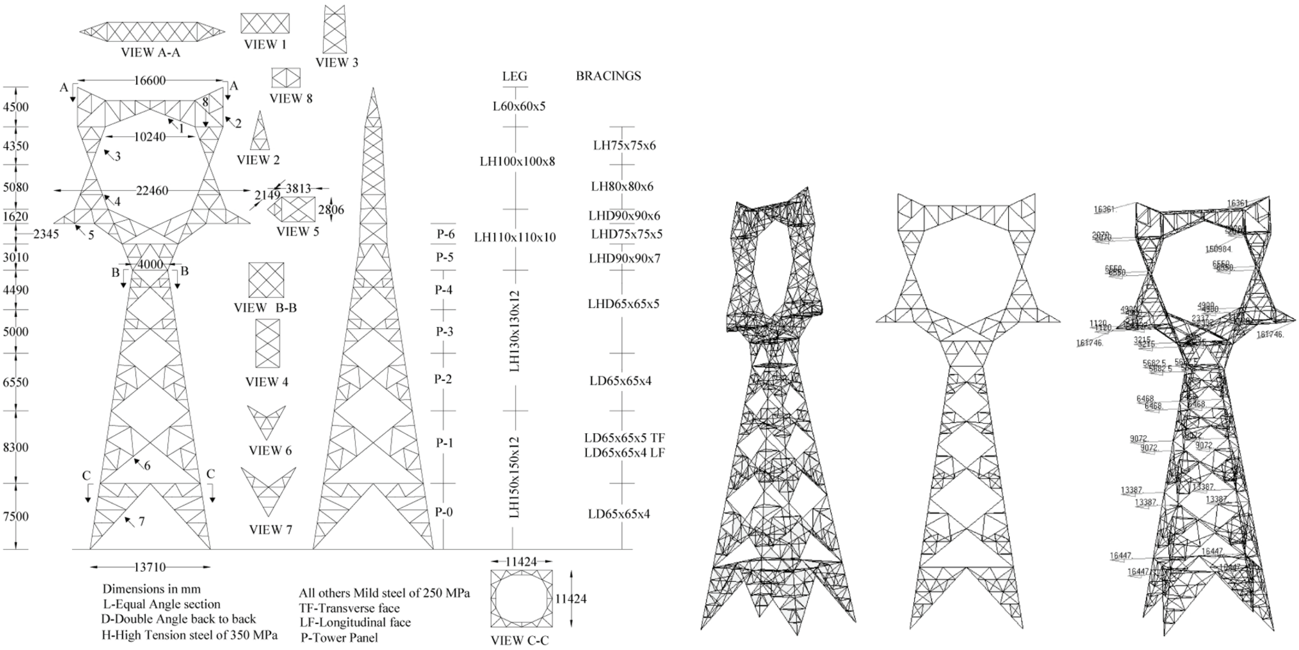

Figure 2. Tower configuration, panel numbers, and finite element (FE) model and loading on a tower.

Box 1. Details of conductor

Basic span: 400 m
Overall diameter: 3.505×10^{-2} m
Cross sectional area: 7.500×10^{-4} m^2
Unit weight: 2.181 kg/m
Ultimate tensile strength: 15,704 kg
Coefficient of thermal expansion: 2.120×10^{-5}/°C
Modulus of elasticity: 6322×10^6 kg/m^2
Shape factor: 1.000
Gust factor: 2.285
Drag factor: 1.00
Everyday temperature: 32°C

Box 2. Details of ground wire

Basic span: 400 m
Overall diameter: 1.098×10^{-2} m
Cross sectional area: 7.362×10^{-4} m^2
Unit weight: 0.583 kg/m
Ultimate tensile strength: 6972 kg
Coefficient of thermal expansion: 1.150×10^{-5}/°C
Modulus of elasticity: 19361×10^6 kg/m^2
Shape factor: 1.000
Gust factor: 2.3865
Drag factor: 1.20
Everyday temperature: 32°C

TL towers are designed for meteorological reference wind speed derived by converting the 3 sec peak gust speed into 1 minute averaging period using a factor[21]. Towers are designed for three reliability levels based on voltage clause. The members are designed based on ultimate stresses. Eccentricity and end restraints in compression member design are accounted by considering the modified slenderness ratio[22].

The literature review shows that the combined effect of wind and dust storms on the TL tower system has not been studied numerically using wind tunnel experiments. In recent years, there is frequent occurrence of dust storms over north India during the pre-monsoon season, causing severe damage to the TL system according to the major power distributors, even though the measured wind speeds are less than the design wind speed. Hence there is a need for studying the effect of dust storms on the stability of the TL system subjected to the combined action of wind and dust.

Tower configuration

In recent years, there is failure of TL towers of different voltage clauses in the northwestern India. For the present study, a single-circuit, delta-type horizontal configuration tower which collapsed in the 765 kV TL system in northwestern India has been considered. The 765 kV line was commissioned in Agra region after the successful completion of full-scale testing and presently in use. The square-based tower is 52.75 m in height, 13.71 m wide at +0 m level and 4 m wide at 32 m hamper level. An IVI conductor configuration is used with 'I-string' for the left and right conductors, and 'V-string' for the middle conductor. Two ground wire systems are provided. Figure 2 shows the tower configuration, dimensions, panel number, FE model and loading on a tower. Boxes 1 and 2 provide details of the conductor and ground wire used.

Wind load

Sag and tension

Sag is the vertical distance between the support points and the lowest point of a conductor. The horizontal distance between the wire supports is called the span of the wire. In TL towers, the significant loads are from the normal and broken conductor conditions. Sag and tension for conductor and ground wire are calculated according to IS 802 (Part 1/Sec 1): 2015 (ref. 21) and CBIP (Central Board of Irrigation and Power) Manual 2014. Sag and tension depend on several factors such as wind pressure, unit weight of wire, thickness, initial tension in the wire, temperature and material properties of wire, etc.

$$S = \frac{wL^2}{8T},$$

where S is the sag of wire (m), w the unit weight of the wire (kg/m), L the length of the wire (m) and T is the final tension in the wire (kg).

Table 1 shows the sag and tension in the conductor and ground wire for the existing design loads. The maximum sag and tension in the ground wire are 11.466 m and 3770 kg and in conductor 14.835 m and 9668 kg respectively, for the existing design wind pressure.

Table 1. Design sag and tension in conductor and ground wire (GW)

Temperature (°C)	P_d (kg/m^2)	Wind	Sag (m)	Tension
Conductor				
32	89.6	100	4.512	9668
85	89.6	0	14.835	2940
GW				
32	89.6	100	3.093	3770
53	89.6	0	11.466	1017

Table 2. Load on tower panels

Panel no.	Transverse load (kg)
P-0	5871
P-1	4779
P-2	3238
P-3	2309
P-4	2028
P-5	1148
P-6	834

Table 3. Design load on conductor and GW

	Normal condition (kg)			Broken condition (kg)		
Wire type	TL	VL	LL	TL	VL	LL
Conductor	13,361	6,234	0	6,114	4,141	15,757
GW	1,259	360	0	561	220	3,073

TL, Transverse load; VL, Vertical load; LL, Longitudinal load.

Wind load on tower body

The wind load on the tower is calculated based on IS 802 (Part 1/Sec 1): 2015 specifications[21]. As shown in Figure 2, the tower is divided into panels. Wind load on each panel is calculated and distributed at the corner nodes of the corresponding panel. Table 2 gives the transverse wind load on the tower for design wind pressure. A well-designed TL tower should withstand transverse and longitudinal loads from the conductor and ground wire. Generally, loads on the tower are calculated for normal and broken wire conditions under different categories like reliability, security and safety requirements. Table 3 gives the loads on the conductor and ground wire under reliability and security requirements.

Finite element analysis

NE-NASTRAN, FE analysis software has been used to study the failure of the tower in detail. The tower members are modelled using beam elements with four sub-elements per member. The beam element is a line element with a defined shape and with stress recovery points. The limit load is reached in FE analysis when the stresses at the maximum stressed point in the member exceed the yield stress. Nonlinear analysis accounting for geometric and material nonlinearity is performed on the tower. The elastic and plastic material property of steel is represented by an elastoplastic bi-linear model with the modulus of elasticity as 2E5 MPa up to yield level and 2000 MPa above yield level. Figure 2 shows the FE model, while Figure 3 shows the schematic diagram of conductor and ground wire points for all critical load combinations considered in the present study. The tower was analysed for all critical design load combinations given in Box 3. Table 4 shows the FE model analysis force in the leg and bracing members for the design loads. The member forces are compared with the design strength.

Design of tower members (elements)

The tower members are designed based on IS 802 (Part 1/ Sec 2): 2016 specifications[22], which are in line with 'Design

Box 3. Critical load cases

Reliability condition
Security LGW broken
Security MC broken
Security LBC broken
Safety condition
Safety LGW broken
Safety MC broken
Narrow front

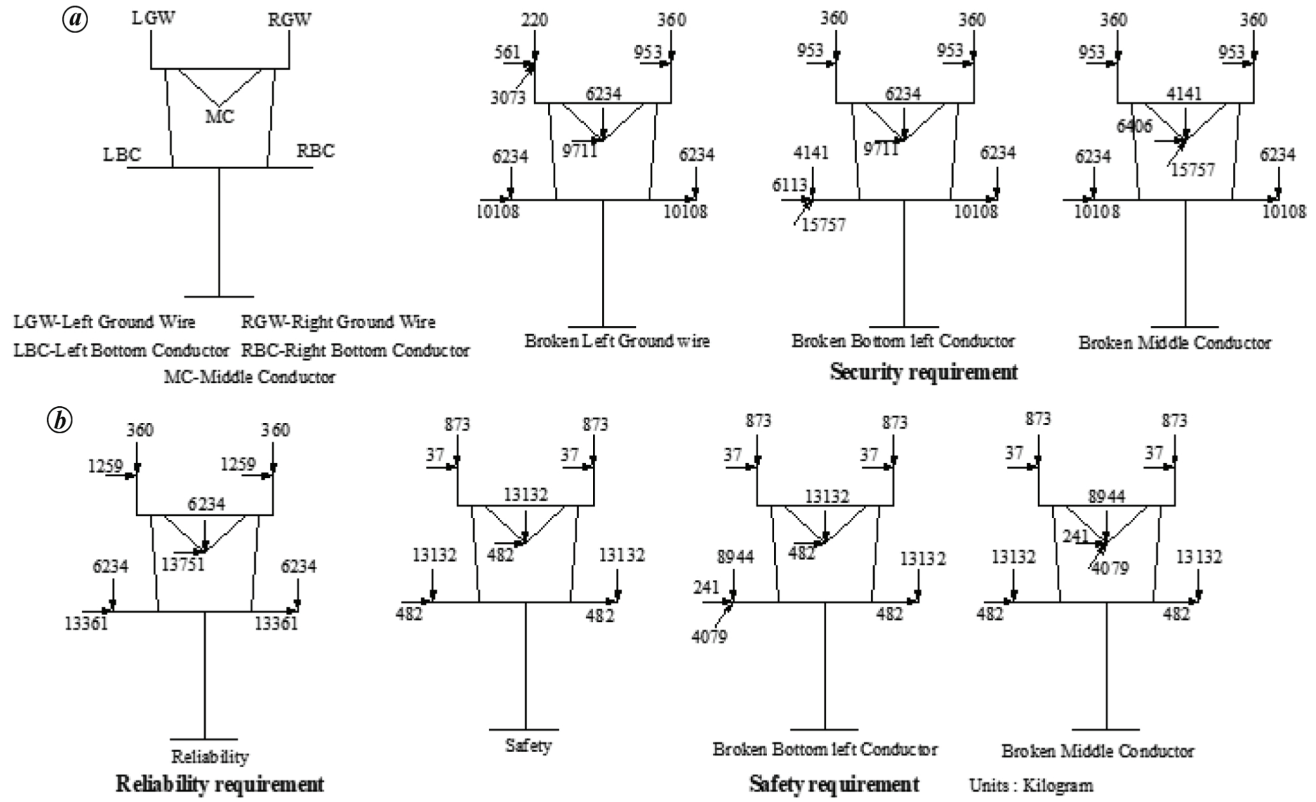

Figure 3. ***a***, Schematic view of conductor and ground wire. ***b***, Load trees: design load for critical load combinations.

Table 4. Analysis of forces in leg and bracing members (design load)

Member size (mm)	Yield stress (N/mm^2)	Slenderness ratio	Member force (kN) 0% of dust particles
Leg members			
L150 × 150 × 12	350	51	983
L130 × 130 × 12	350	52	901
L110 × 110 × 10	350	76	632
L100 × 100 × 8	350	93	205
Bracing members			
T65 × 65 × 5	250	120	98
T65 × 65 × 4	250	121	66
T65 × 65 × 5	350	106	169
T90 × 90 × 6	350	90	105
T75 × 75 × 5	350	89	93
T90 × 90 × 7	350	95	121

L, Equal angle section; T, Back to back angle section.

of lattice steel transmission structures, ASCE 10–15' standard[23]. The effective length of the compression member depends on the eccentricity and end restraint. Based on the end conditions, loading eccentricity and member slenderness ratio, a detailed procedure for modification of slenderness ratio and member stresses accounting for the local plate buckling of angle sections is given in the code. Table 5 shows the capacity of leg and bracing members.

Wind pressure due to dust particles in wind

Guidelines or methodology for calculating the wind pressure on towers subjected to combined wind and dust loads are not available in the literature. In the present study, the density variation method has been adopted for calculating the additional wind pressure due to presence of various percentages of dust particles in the dust storms. The relation between density of air, density of air mixed with dust particles and volume of dust fraction is used.

$$r_{\text{air mix}} = r_{\text{air}} + V_{\text{f}} * r_{\text{dust particles}},$$

where $r_{\text{air mix}}$ is the density of air with dust particles or increased air density due to dust particles (kg/m^3), r_{air} the density of air (kg/m^3), V_{f} the volume fraction/m^3, $r_{\text{dust particles}}$ is the density of dust particles.

The design wind pressure at any height above the mean ground level can be calculated using the relation between wind pressure and wind speed as given in IS 875 (Part 3): 2015 (ref. 20).

$$P = \frac{1}{2} r * V^2,$$

where P is the wind pressure (N/m^2), r the density of air (kg/m^3) and V is the design wind velocity (m/s).

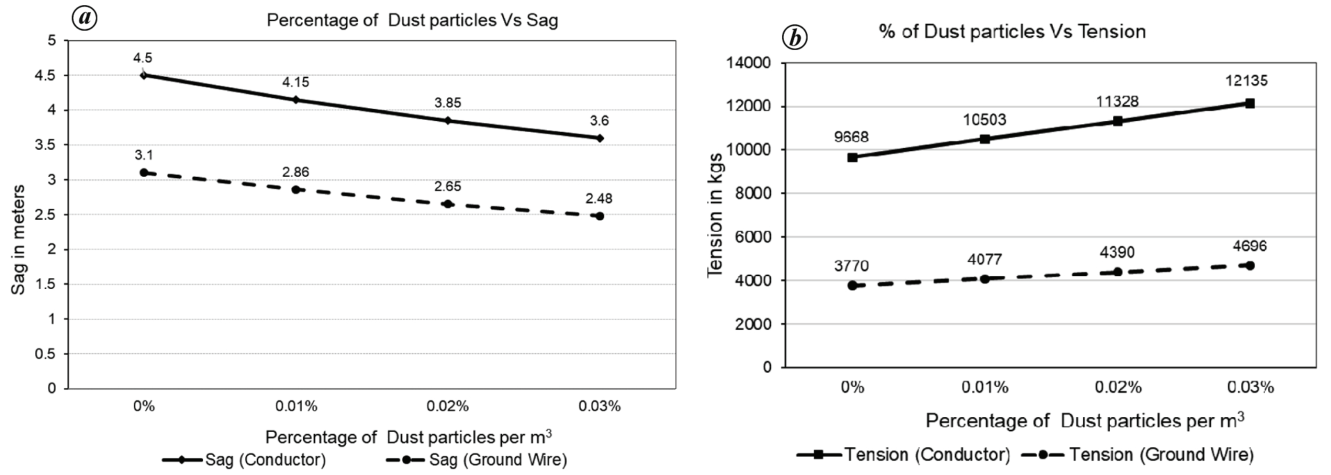

Figure 4. Variation of (***a***) sag and (***b***) tension in conductor and ground wire for different fractions of dust particles.

Table 5. Capacity of leg and bracing members

Member size (mm)	Yield strength (N/mm^2)	Panel number	KL/r	Capacity (kN)
Leg members				
L150 × 150 × 12	350	P-0	51	1051
		P-1	57	1020
L130 × 130 × 12	350	P-2	52	918
		P-3	55	900
		P-4	51	922
L110 × 110 × 10	350	P-5	76	549
		P-6	75	549
L100 × 100 × 8	350	P-7	93	551
Bracing members				
T65 × 65 × 4	250	P-0	110	140
T65 × 65 × 5	250	P-1	120	169
T65 × 65 × 4	250	P-2	108	143
T65 × 65 × 5	350	P-3	115	131
T65 × 65 × 5	350	P-4	94	253
T90 × 90 × 7	350	P-5	90	416
T75 × 75 × 5	350	P-6	89	273
T90 × 90 × 7	350	P-7	95	492

KL/r, Effective slenderness ratio.

Table 6. Variation of wind pressure

Volume fraction of dust (V_f, %)	$r_{\text{air mix}}$ (kg/m^3)	Wind pressure (kg/m^2)
0	1.200	89.64
0.01	1.346	100.41
0.02	1.492	111.30
0.03	1.638	122.19

Therefore, wind pressure depends on the density of air and velocity of the wind. In the present study, considering the density of air as 1.2 kg/m^3, the density of air combined with dust particles has been studied. Volume fractions of 0%, 0.01%, 0.02% and 0.03% of dust particles in air are considered for wind pressure calculations. Since the density of dust particles (loose–dry soil) is high compared to the density of air, minute fractions of dust particles bring significant change in wind pressure. The geological data indicate the presence of sandy loam soil in the river delta region. The density of sandy loam soils is considered as 1460 kg/m^3 in the calculations. Table 6 shows the variation of wind pressure for different volume fractions. Figure 4 shows the variation of sag and tension in the ground wire and conductors for different percentages of dust particles in air. Since sag and tension are inversely proportional to each other, as the sag decreases, tension increases. Figure 5 shows the variation of wind load on tower body and on insulator string respectively, with changing percentage of dust particles.

As the conductor and ground wire tension increases with increased percentage of dust in air, there is an increase in transverse load and longitudinal load in the conductors and ground wires (Figure 6).

Failure description

TL towers may fail due to many reasons such as incorrect design assumptions, improper detailing, material defects, fabrication errors, force-fitting during erection, and are classified as local or structural depending on the failure pattern. Failure of primary or secondary bracing not leading to complete collapse is called local failure. Failure due to leg member stress exceeding its capacity is called structural failure. Towers may fail due to failure of the foundation.

The leg member forces predicted from the linear static analysis for 0.01%, 0.02% and 0.03% of dust particles for the critical load case are compared with the member capacity (Table 7). Figure 7 shows the variation of forces in the leg and bracing members for different fractions of dust in air.

The NL analysis predicts failure of both compression leg members in basic tower level at 94% load in reliability

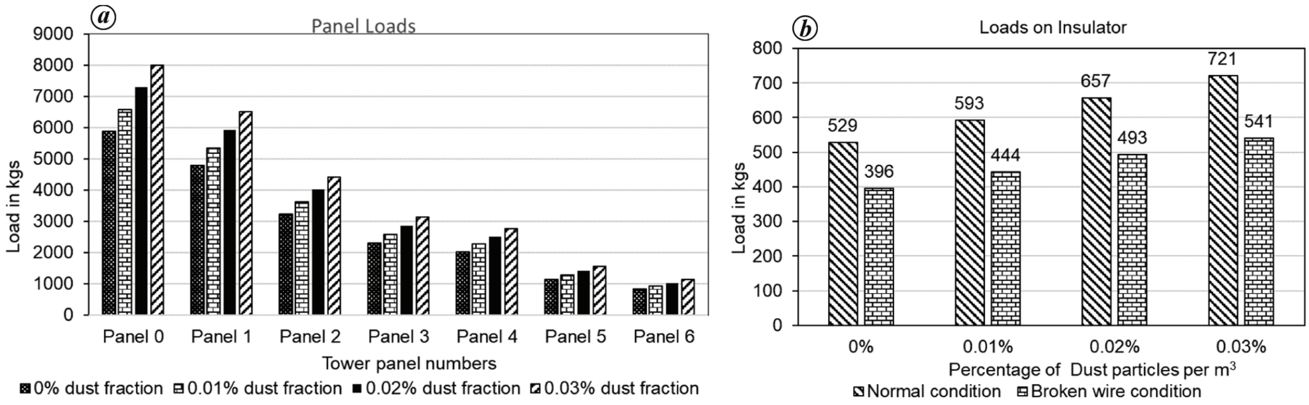

Figure 5. Variation of (***a***) tower panel load and (***b***) insulator string for different fractions of dust particles.

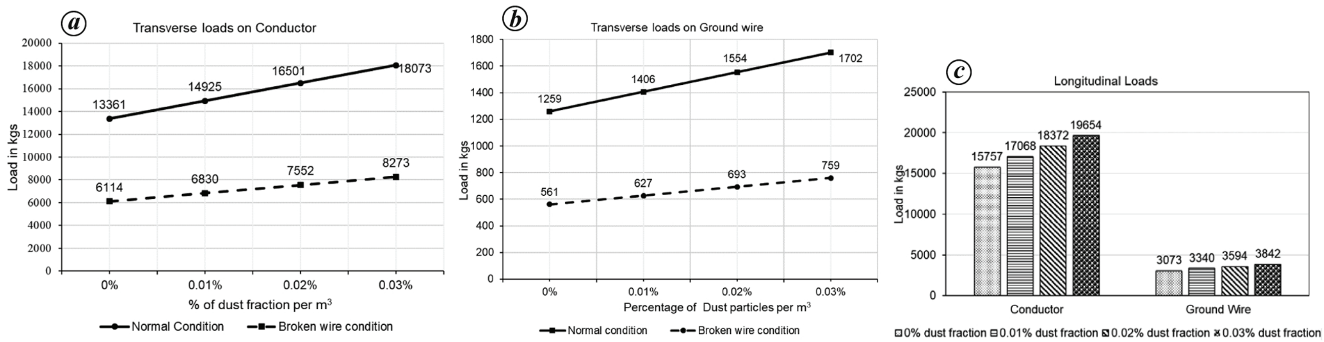

Figure 6. Variation of (***a***) transverse load on conductor and (***b***) ground wire in normal condition (intact) and broken wire condition for different fractions of dust particles. ***c***, Variation of longitudinal load on conductor and GW for different fractions of dust particles.

condition with 0.01% of dust particles (Figure 8 *a*). Failure occurs due to member stresses exceeding the yield stress. It occurs at the same level for reliability condition with 0.02% of dust particles at 86% load (Figure 8 *b*). In the middle conductor broken case with 0.01% of dust particles, failure occurs at 96% load due to one leg subjected to stresses above its capacity (Figure 8 *c*). Right and left conductor broken conditions are less critical for 0.01% of dust particles compared to 0.02%.

Results and discussion

Discussion

Power transmission utilities in northwestern India have reported tower failures during dust storms in the pre-monsoon period from March to May. The failure rate is much higher (55–70%) in suspension-type than tension-type towers. In the northwestern region, TL towers are designed based on IS 802, considering wind zone 4 under IS 875 with wind speed 47 m/s. The other localized high-intensity wind conditions having narrow front, viz. dust storms/thunderstorms, tornadoes and hurricanes are not considered. The suspension towers are not designed for horizontal forces in the longitudinal direction. Hence the failure of one suspension-type tower may lead to adjacent tower failure.

A detailed study was conducted on the failure of a 765 kV delta-type, single-circuit tower subjected to dust storms in the river delta region of northern India. Wind tunnel and numerical studies on the effects of wind associated with dust particles (dust storms) and methodology to evaluate the loads due to dust storms are not available in the literature. Hence for additional wind pressure calculations, the relationship between density of air mix, volume fraction of dust and density of dust particles was considered. In the present study, 0.01%, 0.02% and 0.03% of dust particles/m^3 of air are considered. Variation of sag, tension in conductor and ground wire, wind load on tower body and insulator strings have been studied in detail. The influence of increased wind pressure and the resulting load on the overall performance of the tower have also been studied.

Results

The significant points observed in the present study are listed below.

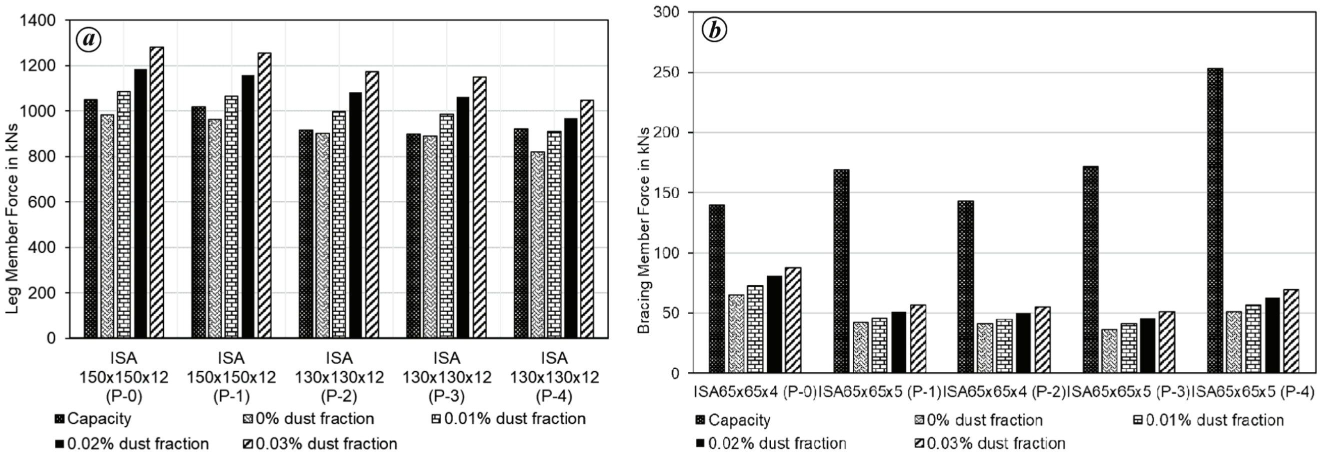

Figure 7. Variation of forces in the (***a***) leg and (***b***) bracing members in different panels of the tower for different fractions of dust particles.

Table 7. Comparison of forces in leg members for different fractions of dust

Leg section (mm)	Yield strength (N/mm^2)	Panel number	KL/r	Capacity (kN)	Member force (kN) for different percentages of dust particles in wind: 0	0.01	0.02	0.03
L150 × 150 × 12	350	P-0	51	1051	983	1087	1184	1283
		P-1	57	1020	963	1066	1159	1256
L130 × 130 × 12	350	P-2	52	918	902	999	1083	1174
		P-3	55	900	889	986	1062	1150
		P-4	51	922	820	912	969	1049
L110 × 110 × 10	350	P-5	76	549	439	501	574	625
		P-6	75	551	386	413	415	431

KL/r, Effective slenderness ratio; L, Equal angle section.

The wind pressure increases by about 10% for every 0.01% increase of dust particles in air/m^3. Since air density increases due to dust particles, wind pressure is directly dependent on air density and velocity.

As wind pressure increases, tension in the ground wire and conductor increases by about 7–8% for every increase of 0.01% of dust particles, since the tension is directly dependent on wind pressure. As a result, the transverse load on the conductor and ground wire increases by 11%, and longitudinal load on the conductor and ground wire increase by 7.5%. Transverse load on the tower body and insulators increase by 10% for every 0.01% increase of dust particles, since it is directly dependent on wind pressure.

The sag is indirectly proportional to tension. Hence sag in conductor and ground wire decreases by about 8% for every 0.01% increase of dust particles. As a result, the leg and bracing member forces increase by about 9.5% for every 0.01% increase of dust particles, resulting in overstressing beyond yield level and failure of the tower.

Suggestions for failure prevention

The towers can be strengthened after identifying the critical members by replacing them with higher size members, adding redundant members to the main members for increasing compression capacity, and providing hip and plan bracings (diaphragm bracing) up to bottom waist level to increase the stability. Periodic inspection and maintenance should be conducted to identify and replace the missing members, washers, nuts and bolts. The holes left in the tower members must be filled with bolts and nuts to increase the strength of members. Presently, towers in India are designed for 50, 150 and 500 return periods according to IS-802, and the option of introducing an intermediate return period can also be considered for ultra high voltage lines.

Conclusion

The results of the detailed studies conducted on the failure of a 765 kV delta-type, single-circuit tower subjected to dust storms indicate that the tower is safe for loads corresponding to the design wind speed (47 m/s). The tower members are overstressed even for wind combined with 0.01% of dust particles, thus causing instability and leading to failure. It is concluded that the wind combined with dust particles significantly affects the tower behaviour. This study emphasizes the need for considering dust particles in storms. It is suggested that in the design

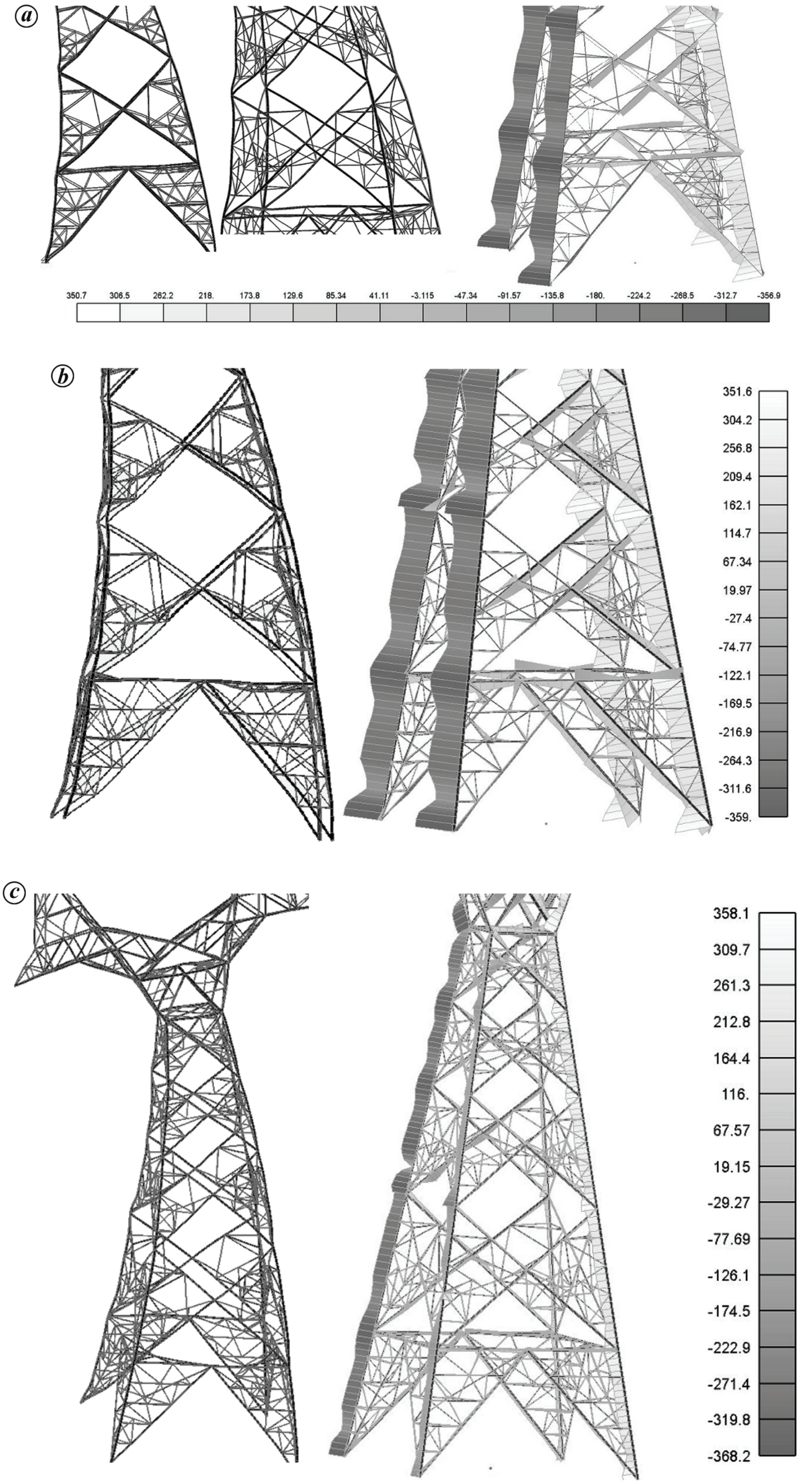

Figure 8. Finite element model failure modes and stress variation in the members at limit load. ***a***, Failure at basic tower and stresses in the members: reliability condition with 0.01% of dust particles in the air. ***b***, Failure at basic tower and stresses in the members: reliability condition with 0.02% of dust particles in the air. ***c***, Failure mode and stresses in the members: middle conductor broken condition with 0.01% of dust particles in the air.

of TL towers for the northwestern region, the effect of additional loads due to dust storms must be considered.

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