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Studies on failure of transmission line towers in testing

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ABSTRACT

The towers are vital components of the transmission lines and hence, accurate prediction of their failure is very important for the reliability and safety of the transmission system. When failure occurs, direct and indirect losses are high, leaving aside other costs associated with power disruption and litigation. Different types of premature failures observed during full scale testing of transmission line towers at Tower Testing and Research Station, Structural Engineering Research Centre, Chennai are presented. Failures that have been observed during testing are studied and the reasons discussed in detail. The effect of non-triangulated hip bracing pattern and isolated hip bracings connected to elevation redundant in 'K' and 'X' braced panels on tower behaviour are studied. The tower members are modeled as beam column and plate elements. Different types of failures are modeled using finite element software and the analytical and the test results are compared with various codal provisions. The general purpose finite element analysis program NE-NASTRAN is used to model the elasto-plastic behaviour of towers. Importance of redundant member design and connection details in over all performance of the tower is discussed.

1. Introduction

The design of transmission line (TL) tower is generally based on minimum weight basis. The towers, in general, are of lattice type consisting of legs, primary/secondary bracings and cross arm members. Structural design of the tower is mainly governed by wind loads acting on conductor/tower body, self weight of conductor/tower and other loads due to icing, line deviation, broken wire condition, cascading, erection, maintenance, etc. Generally the tower is modeled as a pin jointed space truss. Only leg and primary bracings are considered in the analysis and the secondary bracings (redundants) are ignored. Transmission line towers are generally analyzed by linear static analysis methods and the maximum member forces are arrived at assuming that all members are subjected to axial forces only and the deformations are small. The final member sizes are determined by assuming the effective lengths. The members are designed based on the prevailing codes of practice. Bearing type bolted connections are used to connect the tower members with nominal bolt hole clearance of 1.5 mm. Steel equal angle sections with different grades are generally used in TL towers. Prototype testing of transmission line tower is recommended to verify the design and detailing. Most of the power transmission industries all over the world have made proto type testing of TL towers mandatory.

Al-Bermani and Kitipornchai [1] modeled the angle members in the tower as general asymmetrical thin-walled beam column elements. The material non-linearity is modeled based on the assumption of lumped plasticity coupled with the concept of a yield surface in force space. Formex formulation is used for automatic generation of topology, geometry, load and constraint conditions of TL towers. The effect of joint flexibility can be incorporated by modifying the tangent stiffness of the element using an appropriate moment–rotation (M–θ_r) relation for the joint [2]. The effect of nonlinearity is treated as an effective load in conjunction with the applied loads for general equilibrium [3]. The load is modified by a residual force to maintain equilibrium instead of modifying the global tangent stiffness matrix to reflect the extent of nonlinearity in the system. Al-Bermani and Kitipornchai [4] reviewed the current design practices of TL towers and developed a software which includes the geometric and material nonlinearities, joint flexibility and the effects of large deflection for the prediction of the ultimate strength and behaviour of TL towers under static load conditions. Kemp and Behncke [5] conducted a series of tests on cross bracing system widely used in TL towers and concluded that due to dominant effect of end eccentricity, the secant formulation can be used to provide a design formulation for cross bracing. Simple diaphragm bracing systems can be very effectively used in upgrading of old towers. Analytical and experimental studies showed considerable strength improvements using diaphragm bracings [6]. The most efficient diaphragm bracing system predicted from the experimental results was implemented on an existing 105 m high TV tower. Al-Bermani and Kitipornchai [7]

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presented a non-linear analytical technique accounting for both material and geometric non-linearity to predict TL tower failure and calibrated the same with results from full scale tower test conducted on 275 kV double circuit TL tower.

2. Design practice

The members in TL tower are generally subjected to tension or compression forces due to external loads. The design of leg member is reliable, since the assumption of concentric load at both ends of the member is achieved in a real structure due to geometric symmetry of the structure. The eccentricities involved in the bracing member connections are accounted in the form of end-restraint coefficients and hence bracing members design do have certain approximations built into them.

The tower members are generally made of steel equal angle sections. Generally buckling strength of the member about *VV*-axis (minor axis) is considered in the design. If the main member is restrained by a redundant member connected to a relatively rigid member at its other end, then it can prevent *VV*-axis buckling of full member and increase its buckling strength. If buckling about *VV*-axis is prevented using redundant member, then the member has to buckle about its rectangular axis (*XX*-axis) for the same length. This principle is used in the general design practice of TL towers. The capacity of members given in Table 1 are determined based on the buckling formulae given in IS: 802 (Part1/Sec. 2)-1992 [8] and ASCE 10-97 [9] which are formulated in accordance to ASCE manual 52.

3. Failure of transmission line towers

Even though transmission line towers are designed based on the codal provisions, some of them may fail during testing due to many reasons such as incorrect design assumptions, improper detailing, material defects, fabrication errors, force fitting during erection, and variation in bolt strength. The failures occurred at Tower Testing and Research Station, Chennai are classified as structural failure like leg, bracing and redundant failures, detailing and connection failures, material defects and fabrication errors. Generally leg members are designed with slenderness ratio varying from 35 to 50 and at this range the compression capacity is always more or less equal to the net tension capacity of the member. Many failures of the towers are caused by buckling of compression bracing and leg members. The redundant members may also cause failure of main members if it is not properly designed.

4. Present study

Out of 145 full-scale tower tests conducted, 33 towers experienced different types of premature failures. For the present study, five towers are investigated for their failure during testing. Different types of failures that occurred in these five towers are investigated. The member capacities have been worked out for individual cases following ASCE 10-97/IS: 802 provisions and are given in Table 1. The capacity of member calculated based on IS: 802 standard is same as ASCE. To study the failures in detail, nonlinear finite element analysis using NE-NASTRAN was carried out. The member capacities and forces at the time of failure obtained using beam column elements in finite element models are given in Table 1. Member capacities calculated based on BS-8100 [10] standard is compared with ASCE 10-97 and test results in the same table.

Table 1
Comparison of member capacities, analytical and test failure loads.

Tower type	Member details			Failure load in percentage		Non-linear analysis force at test failure load in kN	Member capacity		Failed members
	Size	L/r	F_y	Test	FE NL analysis		ASCE 10-97/IS:802 in kN	BS in kN	
132 kV (0–2°)	ISA 100 × 100 × 8	62	350	100	106	424	441	476	Leg in second panel
	ISA 100 × 100 × 8	64	350			402	433	470	Leg in third panel
400 kV D/C (0–15°)	ISA 150 × 150 × 20	61	350	90	103	1308	1644	1744	Leg in fourth panel
	ISA 55 × 55 × 4	150	255			26	40	36	Horizontal redundant member bearing failure
275 kV D/C 'H' type	ISA 150 × 150 × 18	36	410	62.3	94.4	1011	1943	1980	Leg in first panel
	ISA 150 × 150 × 18	43	410			970	1882	1939	Leg in second panel
	ISA 120 × 120 × 8	150	275			62	192	170	Bracing in first panel
	ISA 90 × 90 × 6	128	275			50	133	108	Bracing in second panel
400 kV (0–2°)	ISA 150 × 150 × 12	61	255	75	96.6	520	774	807	Leg in first panel
	ISA 150 × 150 × 12	58	255			505	785	813	Leg in second panel
	ISA 80 × 80 × 6	182	255			35	65	62	Bracing in first panel
400 kV D/C (15–30°)	ISA 200 × 200 × 20	50	350	100	106	1962	2378	2465	Second panel Leg 4 parts: Leg and brace failure
(a) TC & BC	┘└ 80 × 80 × 6	105	350			267	291	253	
(b) TC & MC (Trial 1)	┘└ 90 × 90 × 6	76	350	80	101	213	375	351	Bracing failure major axis
(c) TC & MC (Trial 2)	ISA 200 × 200 × 20	40	350	95	103	1930	2485	2534	Leg failure (Leg 5 parts)

TC, MC, BC: top, middle and bottom conductors broken.