Earthquake Resistance Capability of Distribution Pole

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SUMMARY:
Past earthquakes have caused extensive damage to the electrical power networks, important lifelines that deliver electric power to residents and businesses in urban and suburban areas. Robust electric power system is essential to maintain uninterrupted power supply during and immediately after earthquake and to assist reconstruction of the damaged buildings and other infrastructure. However, not much care is taken to ensure the seismic resistance capability of mechanical supports like transmission towers and poles by power utilities. This paper brings out the results of comprehensive study involving Tri-axial shake table testing and finite element analysis of low voltage distribution pole.

Key words: Shake table tests, distribution pole, Prototype static tests.

1. INTRODUCTION

In the past, many earthquakes have caused massive damage to the high voltage installations and electrical equipment around the world and disruption in power supply for many days during the critical phase of rescue operation. In addition to the direct loss inflicted by earthquakes by damaging the infrastructure, disruption in electric power supply results in huge loss of revenues, interruption of industrial production and greatly affects the rescue operations. The reliability and safety of electrical transmission and distribution system after an earthquake depend on the seismic response of individual components such as substation equipment, transmission and distribution lines etc., Hence equipment and supporting structures of power generating stations, transmission installations and substations located in seismically sensitive regions / zones have to be designed to withstand possible earthquakes. Transmission and distribution lines are important elements of electric power system. Procedure used to verify the seismic design of equipment includes simulations based on the finite element method combined with either response spectrum or time history analysis and shake table testing. An experimental investigation has been carried out to evaluate the performance of low voltage distribution pole during possible earthquake. One 10 metre height octagonal steel pole was designed considering the maximum wind pressure recommended by the standards, maximum tension in the conductors to be supported by the pole in service and the dead weight of conductors and insulators with in the normal span (between two consecutive poles in the field).

The octagonal steel pole has been tested as per IS 2713(Part-I): 1980 at the Tower Testing Station of Central Power Research Institute, Bangalore. The Pole was mounted vertically true to the plumb on rigid footings on the Test Bed of Tower Testing Station. The pole was tested applying the design loads comprising of wind load on the pole and tension in the conductors. Arrangement was made to measure the deflection at a point 600 mm below from top of the Pole. The deflection reading was taken before attachment of any loading arrangement as an initial/reference reading. The pole withstood the design loads for duration of 300 seconds.

The assessment of the seismic vulnerability of electrical power equipment is a very complex issue due to the non-deterministic characteristics of the seismic action and the need for an accurate prediction of their seismic responses. The most commonly used methods for seismic qualification are Finite Element Analysis and Shake Table Tests. The octagonal pole was mounted on the shake table. The tests on a shaking table have the advantage of being dynamically similar to a real earthquake event. Exploratory vibration tests are carried out on the pole to determine its dynamic characteristics. This test is performed as a slowly swept sinusoidal vibration test in each axis. The equipment responses are measured to determine resonances. Strain gauges and accelerometers were mounted at identified locations. Seismic tests were carried out on the distribution pole. The seismic response of the pole was determined by conducting shake table tests

The dynamic characteristics of the pole have been evaluated using software NASTRAN. The resonance frequencies and mode shapes have been determined. The analytical results are compared with shake table test results. The earthquake resistance capability of distribution pole was determined by both analysis and shake table tests. The analytical and experimental results are analyzed and the conclusions drawn are clearly brought out in this paper.

2. PROTOTYPE TESTING OF POLE

Mechanical supports like transmission line towers and poles are designed for wind loads, snow loads, tension in the conductors and loads due to deviation. Different field conditions are simulated during prototype testing viz., service conditions, security condition and safety condition. All the design loads are applied as equivalent static loads with appropriate safety factors, though wind loads and unbalanced loads induced on the supports during broken wire condition are dynamic in nature. Though many advanced software are available to design these support structures, it is mandatory to test one full scale tower or pole in each type to confirm its capacity to withstand critical loads.

A typical distribution steel pole of height 10 m has been taken up for this comprehensive study to evaluate the withstand capacity of the pole in resisting seismic loads. The octagonal steel pole is mounted on the test bed by welding the pole to the base plate. Utmost care is taken to ensure verticality of the pole. Arrangement was made to measure the deflection and apply load at a point 600 mm below from tip of the Pole as shown in Figure 2.1. The deflection reading was taken before attachment of any loading arrangement as an initial/reference reading. A scale is mounted at the point of load application.

Figure 2.1. Prototype testing of Steel Pole

The design load is applied gradually on the pole through wire rope connected to a electrical winch. The deflection of the pole is recorded using theodalite before application of any load and at different percentage of loading. After applying 100% of design load, the pole is observed for a period of 300 seconds. After release of loads, final deflection reading was measured. The pole withstood the design loads without undergoing any failure. The net deflection measured at point of application is listed in Table 2.1. This prototype test confirms its mechanical strength to withstand the critical loads expected to act on the pole during its service life in the open environment. The design load applied on the tower during testing does not include seismic loads. In order to evaluate seismic resistance of the pole to design response spectra corresponding to Zone IV and Zone V recommended in IS 1893:2002, shake table test is carried out.

Table 2.1: Deflection of pole

Sl. No	Percentage of loading	Deflection (mm)
1	45% of working load – 241 kg-f	157.5
2	100% working load - 535	299
3	137% of working load – 733 kg-f	318

3. SEISMIC QUALIFICATION APPROACH

The seismic qualification of equipment and structure should demonstrate their ability to perform its safety function during and after the time it is subjected to the forces resulting from earthquakes. The most commonly used methods for seismic qualification are grouped into four general categories that

- Predict the equipment's performance by analysis
- Test the equipment under simulated seismic conditions
- Qualify the equipment by a combination of test and analysis
- Qualify the equipment through the use of experience data

Each of the preceding methods or other justifiable methods may be adequate. The choice of selection of method to verify the ability of the equipment to meet the seismic qualification requirements is generally based on the practicality of the method for the type, size, shape and complexity of the equipment configuration. The analysis method is not generally recommended for complex equipment that cannot be modeled to adequately predict its response. Analysis is acceptable only if it is not possible to conduct shake table testing due to limitation of the test system.

3.1 Shake Table Test

The most natural testing concept is the use of a shaking table. The equipment to be tested is fixed to a moving platform called shaking table to which a motion history representative of past seismic events or artificial time history is applied.The test on a shaking table has the advantage of being dynamically similar to a real earthquake event.

Seismic ground motion occurs simultaneously in all directions in a random fashion. However, for test purposes, single-axis, biaxial and tri-axial tests are allowed. If single-axis or biaxial tests are used to simulate the three-dimensional environment, they should be applied in a conservative manner to account for the absence of input motion in the other orthogonal direction(s). The simulation if only in single or biaxial then the tests need to be done mounting the specimen along different axes and hence many a times the specimen fails due to fatigue. Among different methods recommended in the relevant codes, tri-axial test is the most suitable since earthquake produces random motions simultaneously in all three directions. Earthquake Engineering Laboratory of CPRI has a state-of-the-art tri-axial shaker system for earthquake simulation.

The octagonal steel pole (test specimen) is mounted on the Tri-axial shake table as shown in Fig.3.1. Resonance search tests (Sine sweep tests) are carried out in each axis to identify the resonant frequencies. The test parameters of the sine sweep test are given in Table 3.1. The resonant frequencies and structural damping are identified from the response of the specimen recorded using accelerometers. The resonant frequencies are shown in Table 3.2.

Table 3.1: Resonance search test parameters

a) Type of vibration	Sinusoidal sweep
b) Axis of vibration	X, Y & Z – axis individually
c) Frequency (range)	1.0 to 50 Hz
d) Acceleration (Peak)	2.0 m/s^2
e) Sweep rate (Logarithmic)	1.0 octave/minute
f) Number of Sweeps	One up sweep per axis

Figure 3.1. Steel pole mounted on shake table

The design spectrum for testing the distribution pole has been obtained as per the recommendations of IS 1893 (Part1): 2002 titled "Criteria for Earthquake Resistant Design of Structures". For the purpose of determining seismic forces India is classified into four seismic zones i.e Zone II, Zone III, Zone IV and Zone V. The standard specifies the forces for analytical design and design spectrum for testing of structures corresponding to the type of soil at site and damping of the structure. The Design acceleration spectrum for vertical motions had been taken as two-thirds of the design horizontal acceleration spectrum as per the codal recommendations. In order to simulate the most critical condition for design validation the soil at site is considered to be soft soil. The Design test spectrum for Zone IV and Zone V are shown in Fig. 3.2 and Fig. 3.3 respectively. Seismic tests were carried out on the pole simulating Design Response spectra of Zone IV and V. The response of the pole was recorded. The maximum stress induced at the base of the pole is evaluated. The pole withstood the seismic loads without undergoing any failure or deformation.

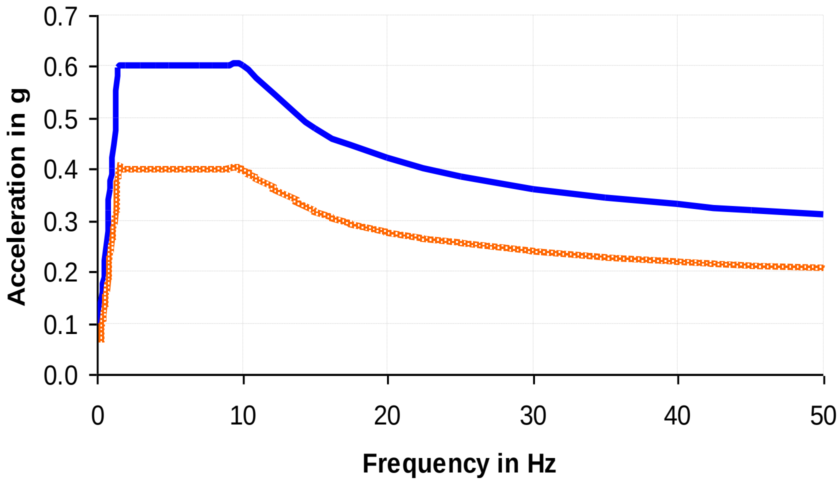

Figure 3.2. Design test spectrum for Zone IV

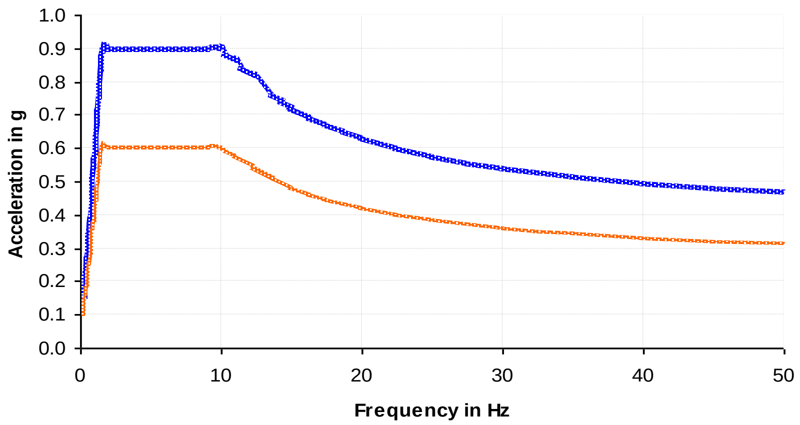

Figure 3.3. Design test spectrum for Zone V

3.2 Finite Element Analysis

The distribution pole was modeled and analysed using FEA software NASTRAN. The pole is of 10m height and having octagonal cross section. The physical dimensions of the pole and mounting arrangement is shown in Fig.3.4. The distribution pole is modeled using four noded shell elements CQUAD4. Total number of nodes is 71770 and number of elements is 12361 in the FE modelling. Frequency analysis was carried out to identify the resonant frequencies (modal frequencies) and mode shapes. The damping value obtained from the shake tests is used in the analysis. The resonant frequencies within the frequency range 1 Hz to 50 Hz are shown in Table 3.2.

The seismic response of the pole to the design response spectrum corresponding to Zone IV and Zone V of IS: 1893-2002, "Criteria for Earthquake Resistant Design of Structures" is evaluated. The variation stress induced in the pole along its length and across the cross section is determined. The maximum stress induced at the base of the pole for the response spectrum corresponding to Zone IV and Zone V is evaluated and shown in Table 3.3.

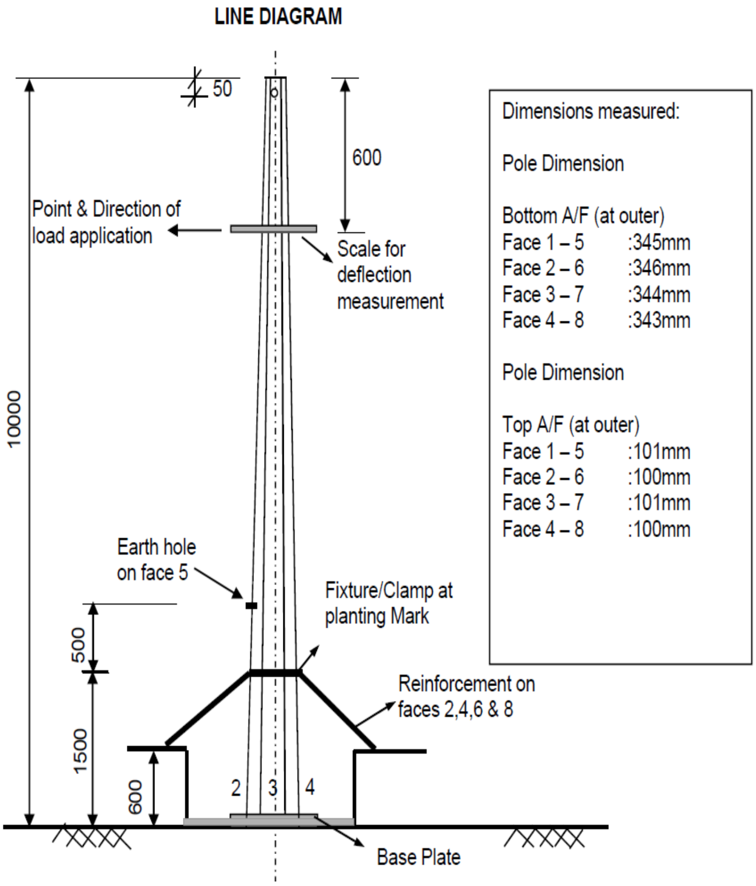

Figure 3.4. Physical dimensions and mounting arrangement of pole.

Table 3.2 Resonant Frequencies

	1 mode		2 mode		3 mode	
	X axis	Y axis	X axis	Y axis	X axis	Y axis
Exp	2.0	2.0	11.5	11.5	32	32
FE modal	1.94	1.94	11.4	11.4	31.1	31.1

Table 3.3. Maximum stress induced at base of the pole

Sl.No	Zone	Maximum stress induced (MPa)	
		Experiment	FE Analysis
1	Zone 4	70	66
2	Zone 5	116	119

4. RESULTS AND DISCUSSIONS

The resonant frequencies obtained from the Experimental investigation using Shake table and analysis using NASTRAN software are compared in Table 3.2. The damping coefficients obtained from shake table tests are used in finite element modal analysis. The resonant frequencies obtained from the analysis compare well with the experimental values. It clearly validates the accuracy of finite element model developed using the above software. The maximum stress induced at base of the pole obtained from shake table tests and analysis using NASTRAN is tabulated in Table 3.3. The results are closely matching.

The response time history recorded during shake table test and the corresponding time history obtained from the finite element analysis are plotted in Fig.4.1. It clearly confirms the adequacy of numerical simulations.

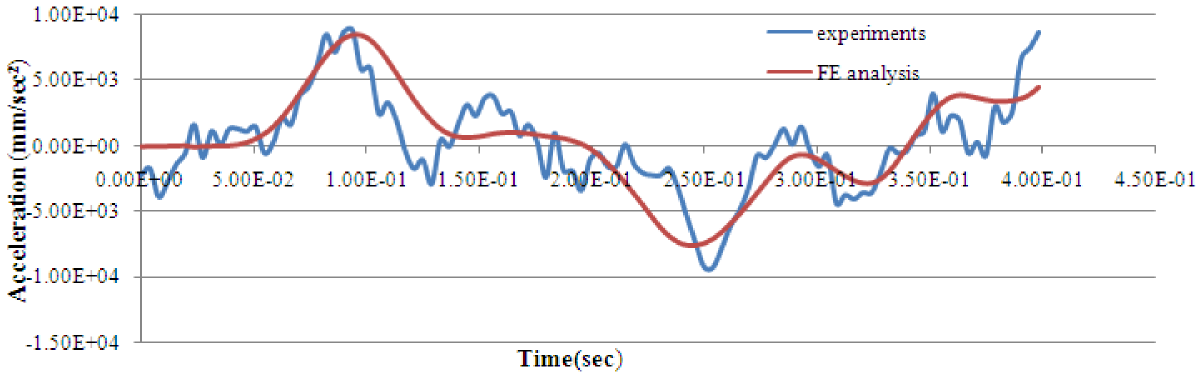

Figure 4.1. Response Time history

The pole that had been designed considering the wind loads and tension in the conductors with adequate factor of safety as per IS 2713(Part-1):1980 "Specification for tubular steel poles for overhead power lines" withstood seismic loads corresponding to Zone IV and Zone V. In the case of distribution poles the maximum wind load is more critical than the seismic loads. Seismic analysis is adequate and no need to carry out shakes table tests.

5. CONCLUSIONS

Shake table tests have been conducted to determine the seismic performance of octagonal steel distribution pole. Finite element model of the pole was developed and its seismic response was obtained using NASTRAN software. Results of analytical and experimental studies on seismic response of the distribution pole are brought out in this paper. Results of Finite element analysis compare well with that of shake table tests. This study demonstrates that the distribution pole can be modeled and analyzed with sufficient accuracy using finite element software like NASTRAN. Though Standards do not recommend any seismic qualification tests for the mechanical supports, Power utilities while designing the distribution poles and Transmission line towers may consider seismic loads in the analysis to ensure that these structures can withstand all the critical loads including seismic loads without undergoing any structural failure or deformation as it is not possible to carry out any tests to qualify these structures for seismic loading. This will help the utilities to ensure uninterrupted power supply during and immediately after severe earthquake and to assist reconstruction of damaged lifeline structures and other human built environment.

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REFERENCES

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