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Reliability Analysis of Compression Struts in Lattice Towers

P. Manikandan[1], R. P. Rokade[2], A. Sivakumar[3]

[1]*M-Tech Project student, VIT University Vellore – 632014*
[2] *Principal Scientist, CSIR-Structural Engineering Research Centre, Chennai – 600113*
[3] *Professor and Head of Structural Engineering Department, VIT University Vellore – 632014*

E-mail: manims91@hotmail.com

***Abstract*--Conventionally Transmission Line (TL) towers are steel lattice structures made from hot rolled steel angles. The TL towers are designed for various loads e.g. atmospheric generated loads, gravity loads, mechanical loads, etc. The governing load for TL tower design is wind generated loads. The wind is uncertain in nature and may vary in time and space which can be predicted with certain probability. Further the material properties of hot rolled steel angles may vary depending on various parameters involved in manufacturing process. In this paper, an attempt has been made to consider these uncertainties for the design of TL tower members. The studies are limited to the design of compression strut as per IS: 802 (Part 1/sec 2):1992. First Order Second Moment (FOSM) method is used for calculation of reliability index (β) and failure probability (P_f) of compression strut in Lattice tower. The failure probability calculation methodology is demonstrated for lattice tower compression strut.**

***Keywords*-- Transmission Line (TL) Towers, reliability Index (β), failure probability (P_f), First Order Reliability Method (FORM), First Order Second Moment (FOSM).**

I. INTRODUCTION

In a transmission line network various types of support structures are used e.g. Self supporting lattice towers, guyed towers and monopoles. The main purpose of the TL towers is to support the conductors and ground wires. The lower profile is designed to maintain suitable clearance distance between bottom conductor and ground level, further the cross arm positioning provides electrical clearance between conductors in vertical and horizontal direction. Considering the structural stability, economy and ease in construction, the lattice steel Transmission Line towers are most suitable support structures for TL system up to 800 KV. The lattice steel towers comprises of primary and secondary members, the primary members are leg and bracing members which will be designed to support the vertical and lateral loads acting on the tower and transfer them to the foundation.

Secondary members are providing intermediate support to the primary members, thereby reducing the unbraced length. Latticed towers are generally fabricated using steel angle sections. The members in the TL towers are generally subjected to reversal of forces caused by lateral wind loads.

The construction cost of these towers is around 30-40% of the total TL project cost and hence it becomes the important component in the TL system. TL towers are designed for various loads such as climatic loads, construction and maintenance load and unbalanced tension due to the conductor breakage. The governing load for TL tower design is wind generated loads. The wind is uncertain in nature and may vary in time and space which can be predicted with certain probability. Conventionally TL towers are steel lattice structures made from hot rolled steel angles Steel angle sections with different grades such as mild, high tensile and super high ensile steels are generally used in the manufacture of the TL tower members. Further the material properties of hot rolled steel sections may vary depending on various parameters involved in the manufacturing process.

Though the TL towers are designed using Indian Standard 802 (part 1/ sec 1) & (part 1/ sec 2): 1992, many failures observed during prototype testing. This is due to uncertainties involved in design, detailing and fabrication practices. Number of uncertainties are present in the structural design; these may be related to inherent variability such as material properties (yield strength of steel, ultimate strength of steel, elastic modulus of steel, etc.), dimensions and loads (wind, gravity, unbalanced tension). Ranganathan, (1990), explained the procedure for calculating the reliability index (β) and probability of failure (P_f) using FOSM method for the linear failure function. The linearization using Taylor's series expansion about the mean point was provided for non linear failure function. Diniz, (2010), explained the presence of uncertainties in almost all variables related to the structural response (material properties, geometries, predictive models, loads, etc.).

The general procedure for calculating the reliability index (β) and probability of failure (P_f) was given for different reliability methods. Deoliya, (2012), has provided methodology for carrying out the vulnerability analysis of microwave antenna tower by considering the uncertainties of the wind speeds and the strength of the cross section of the steel members. Krishnan, et. al., (2006), has done the reliability analysis of the Transmission Line tower, considering the uncertainties in the wind speeds, drag co-efficient (C_d), yield strength (F_y) and ultimate strength (F_u). First Order Reliability Method was used to calculate the tower failure under the normal and broken wire condition. Deoliya, and Datta, (2001), has carried out the reliability analysis of the antenna tower against cumulative fatigue damage failure. FOSM method of reliability analysis and weibull distribution was considered to calculate the reliability of the member and comparisons were made for the reliability estimates. The IS: 802 (part 1/ sec 2):1992 design standards for the Transmission line towers provides the capacity calculation using allowable stress in compression. The stress is calculated for the slenderness ratio considering the effect of end restraints.

In this study an attempt has been made to consider these uncertainties for the design of TL tower members. The design of compression member is based on the guidelines of design standard IS 802 (part 1/sec 2):1995. The reliability index (β) and failure probability (P_f) for compression strut in lattice tower is calculated using FOSM method.

II. DESIGN OF TRANSMISSION TOWER MEMBERS

The IS 802 (part 1/sec 2):1992 provides the following formulation for compressive stress on the gross-sectional area of axially loaded compression members

$$F_a = \left[1 - \frac{1}{2}\left(\frac{KL/r}{C_e}\right)^2\right] \times F_y \quad \text{when } \frac{KL}{r} \leq C_c \qquad (1)$$

$$F_a = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2} \qquad \text{when } \frac{KL}{r} > C_c \qquad (2)$$

Where, $C_c = \pi\left(2E/F_y\right)^{\frac{1}{2}}$

F_Y - yield stress of the material (MPa)

E – Modulus of elasticity of steel (MPa)

L/r- maximum slenderness ratio = unbraced length / radius of gyration

K-effective length coefficient

The angle members have to be checked for the local buckling considerations. If the ratio of the largest width to the thickness (w/t) is more than $210/\sqrt{F_y}$, the value of (F_y) will be reduced in accordance with the provision of The IS 802 (part 1/sec 2):1992.The above formulas indicate that the allowable compressive stress largely depends on the effective slenderness ratio (KL/r) and the yield strength of the material (F_y). However, it may be noted that F_y influences the compressive stress for short members only (KL/r < Cc). For the long members (KL/r > Cc), the allowable compressive stress is unaffected by the material strength.

The slenderness ratio is calculated for different modes of buckling and the maximum value is considered for the allowable compressive stress calculation. The effective length coefficient K modifies the member slenderness ratio for different framing eccentricity conditions at the connection. The code considers the framing eccentricities for leg, bracing and cross arm members in the inelastic range of buckling. In the elastic range of buckling and restrained condition for rotation is considered separately for leg and bracing members. The limiting values of the maximum slenderness ratios for various members are given as follows

- ✓ Leg members, ground wire peak member and lower member of cross arm in compression -120
- ✓ Other members carrying computed stress - 200
- ✓ Redundant members and those carrying nominal stress – 250

III. FIRST ORDER SECOND MOMENT (FOSM) RELIABILITY METHOD (RANGANATHAN, 1990)

The basic aim of the structural reliability is to find the probability that the strength R will be larger than the load S throughout the life of the structure, i.e. P(R>S). Safety margin is defined as M=R-S. Since R and S are random variables, M is also a random variable. Failure corresponds to M<0 and the corresponding probability can be computed if the failure surface equation of M is known. If the variables R and S show the normal distribution, M also corresponds to normal distribution with mean μ_M and standard deviation σ_M, given by

$$\mu_M = \mu_R - \mu_S \qquad (3)$$

$$\sigma_M = \sqrt{(\sigma_R^2 + \sigma_S^2)} \qquad (4)$$

Where, μ_R and μ_S, and σ_R and σ_S are the mean and standard deviation of variables R, S

The probability of failure (p_f) can be computed as,

$$\beta = \frac{\mu_M}{\sigma_M} = \frac{\mu_R - \mu_S}{\sqrt{(\sigma_R^2 + \sigma_S^2)}} \qquad (5)$$

$$P_f = \Phi(-\beta) = 1 - \Phi(\beta) \qquad (6)$$

Where, Φ is the cumulative distribution of the standard normal variable.

β is the reliability index.

From the above equation, β is defined as the reliability index or safety index. Larger the β value, smaller the probability of failure (P_f).The above mentioned failure function is a linear combination of the basic variables. However, this failure function may not be true for most of the practical cases when M is a nonlinear function. To overcome this problem, the approximate values of μ_M and σ_M of the failure function are obtained using Taylor's series expansion of linearised safety margin M.

In FOSM method of reliability analysis, the basic variables are described using their first and second moments. In order to find the Mean and Variance values of failure function, the first order approximation is used. Further the reliability index or safety index is computed purely on the values of the mean and standard deviation of the basic variables. If the first and second moments and the correlation structures of all basic variables are known, then the probability of failure can be computed. Hence this method is known as first order second moment method. In case of the nonlinear failure functions, linearization is done using Taylor's series expansion to determine the approximate values of μ_M and σ_M as follows

$$M = g(X_1, X_2 \dots, X_n) \qquad (7)$$

Using the Taylor's series expansion about the Mean point,

$$X^* = (X_1^*, X_2^* \dots, X_n^*) \qquad (8)$$

$$M = g(X_1^*, X_2^* \dots, X_n^*) + \sum_{i=1}^{n} \left(\frac{\partial g}{\partial X_i} \,|\, X^*\right) (X_i - X_i^*) + \sum_{i=1}^{n} \left(\frac{\partial^2 g}{\partial X_i^2} \,|\, X^*\right) \frac{(X_i - X_i^*)^2}{2} + \cdots \qquad (9)$$

Recall that $\left(\frac{\partial g}{\partial X_i}\right)_{X^*}$ means that $\left(\frac{\partial g}{\partial X_i}\right)$ is evaluated at X^*, after neglecting the higher order terms, we get,

$$M = g(X_1^*, X_2^* \dots, X_n^*) + \sum_{i=1}^{n} \left(\frac{\partial g}{\partial X_i}\right)_{X^*} (X_i - X_i^*) \quad (10)$$

For expansion about mean point, substitute $X_i^* = \mu X_i = \mu_i$

$$\mu_M = E[g(X)] \simeq g(\mu_1, \mu_2, \mu_3 \dots., \mu_n) \qquad (11)$$

Since $E(X_i - \mu_i) = 0$

$$\sigma^2_M = \text{Var}\,[g(X)] \simeq \text{Var}[g(\mu_1, \dots.. \mu_n)] + \text{Var}\left[\sum_{i=1}^{n} \left(\frac{\partial g}{\partial X_i}\right) |\, \mu\, (X_i - \mu_i)\right] \quad (12)$$

$\left(\frac{\partial g}{\partial X_i}\right) |\, \mu$ represents $\frac{\partial g}{\partial X_i}$ evaluated at μ_{X_1}, μ_{X_2} ....

For statically uncorrelated random variables, X_i,

$$\sigma_M^2 = \text{Var}[g(X)] \simeq \sum_{i=1}^{n} \left[\frac{\partial g}{\partial X_i} \,|\, \mu\right]^2 (\sigma_i)^2 \qquad (13)$$

Where, $\frac{\partial g}{\partial x}$ is the partial derivative for the basic variables at the mean point.

IV. PRESENT STUDY

The present work involves calculation of probabilities of failure for Transmission Line tower members in compression.

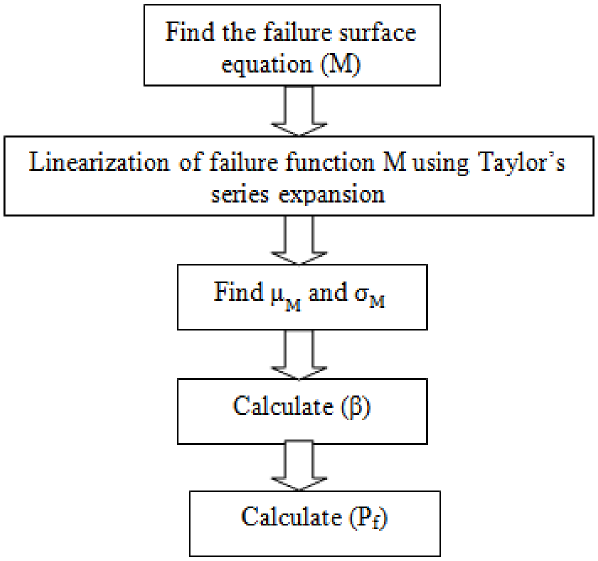

Fig.1. Flow diagram for FOSM reliability method

The FOSM method of reliability analysis is used to calculate reliability index (β), probability of failure (P_f) for the buckling capacity of lattice TL tower members. The calculation steps are represented in the form of flow diagram as given in Fig.1.

The TL tower members in bottom most panel and top lower cross arm are considered in this study are leg member, bracing member and cross arm member. The forces and design details are given in Table 1.

Table 1 Design calculations.
F_y (HT) = 353.0 MPa, F_y (MS) = 245.1 MPa, E = 2.047×10^6 MPa

Member	Section (mm)	Length (mm)	Compressive force (N)	Area mm^2	r_{min}	L/r_{min}	KL/r_{min}	Compression capacity (N)	F.O.S
Leg	HT 130×10	1521.8 divided in 5 parts	730952.91	2512	25.7	59.21	59.21	748300	1.02
Bracing	MS 75×5	1811.8 divided in 5 parts	77077.17	727	14.6	124.0	123.16	94597	1.22
Cross-arm Lower member	HT 90×6	1827.3 divided in 3 parts	199466.73	1047	17.5	104.4	108.31	176440	0.88

The leg member designed above is for the design criteria $KL/r_{min} = L/r_{min}$, considering the fact that both the flanges are connected in butt joint configuration of bolted connection and load is assumed to be concentric loading. The bracing member design considers eccentricity in inelastic range of buckling and the effects of end restraints as rotation for the single flange connection with leg member, hence the $KL/r_{min}=60+0.5\times L/r_{min}$ for $L/r_{min} \leq 120$ or $KL/r_{min} = 28.6+0.762\times L/r_{min}$ for $L/r_{min} > 120$.

Generally the lower member of cross arm is designed in the inelastic range of buckling at one end and normal framing eccentricity at the other end, hence the $KL/r_{min} = 30+0.75\times L/r_{min}$ for $L/r_{min} \leq 120$.

In Table 1, the factor of safety for bracing member is the highest, whereas for leg member the capacity calculated as per codal provisions is almost equal to design force. The capacity of the cross arm member is 12% lesser than the design force and hence the member design is inadequate, and it requires redesign of section.

4.1.0. Failure Probability calculation

In order to find the failure probability of the compression member, performance function has to be formed. The general form of the performance function is

$$M = R - S \qquad (14)$$

Where, M is the safety margin,
R is the resistance of the structure
S is the loads acting on the structure.

For the compression members, the failure function is written in the following form,

$$M = \left[1 - 0.5\left(\frac{L}{r \times \pi\left(\sqrt{\frac{2 \times E}{F_y}}\right)}\right)^2\right] \times F_y \times A - S \qquad (15)$$

In the above equation the first part in RHS indicates the capacity of the section and the S indicates the loads (S) acting on the section. On simplification, the above equation can be reduced into the following form, which is the performance function for the compression member.

$$M = \left[F_y \times A - \frac{0.5 \times L^2 \times A \times {F_y}^2}{r^2 \times \pi^2 \times 2 \times E}\right] - S \qquad (16)$$

In the failure function (M) of the compression member, load (S), Area of the section (A), radius of gyration (r), Modulus of Elasticity (E) and Yield stress of the steel (Fy) are considered as the random variables. The co-efficient of variation is assumed as 10% for all the variables. The random variables are assumed to be statistically uncorrelated. The mean and standard deviation values for the random variables are obtained using the Taylor's series expansion at the mean point since the failure function is non linear. The approximate values of μ_M and σ_M of the failure function are given as,

$$\mu_M = \left[\mu_{F_y}\mu_A - \frac{0.5\, L^2 {\mu_{Fy}}^2 \mu_A}{{\mu_r}^2 \pi^2 2 \mu_E}\right] - \mu_S \qquad (17)$$

$$\begin{aligned}{\sigma_M}^2 = &\left(\frac{\partial M}{\partial S} \mid \mu\right)^2 (\sigma_S)^2 + \left(\frac{\partial M}{\partial F_y} \mid \mu\right)^2 (\sigma_{F_y})^2 \\ &+ \left(\frac{\partial M}{\partial A} \mid \mu\right)^2 (\sigma_A)^2 + \left(\frac{\partial M}{\partial E} \mid \mu\right)^2 (\sigma_E)^2 \\ &+ \left(\frac{\partial M}{\partial r} \mid \mu\right)^2 (\sigma_r)^2 \qquad (18)\end{aligned}$$

The reliability index (β) and the probability of failure (P_f) for the compression members are obtained using the equations (5) and (6) as provided in the Table 2.

Table 2
FOSM analysis for TL tower members

Member	Section	Capacity (N)	Reliability index (β)	Probability of failure (P_f)
Leg	HT 130×10 mm	748300	0.1389	0.44838
Bracing	MS 75×5 mm	94597	0.7210	0.23576
Cross arm	HT 90×6 mm	176440	-0.1923	0.57535

From Table 2, it is observed that the failure probability for cross arm member is very high and the same for bracing member is the lowest. For leg member it falls in between the bracing and cross arm member, which is in agreement with the trend shown by the Factor of Safety values given in Table1.

V. CONCLUSIONS

- The methodology to calculate probability of failure (P_f) using FOSM method of reliability analysis is provided for TL tower members.
- The failure probabilities calculated using FOSM method are in order with the codal provisions and factor of safeties available in member design.

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