Structural Reliability Assessment of Pratt Truss with Post-Tensioning for Strengthening and Rehabilitation.

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Abstract - *More than 40% of the nations' bridges are structurally and/or geometrically deficient. Deficiencies that are numerous in bridges, including uncertain in loads capacity, and geometry. Damage to bridge members occurs due to accidents, excessive loss of the member cross-sectional area because of corrosion, etc. Some of such deficient bridges are in service with restrictions over speed and/or load and some are out of service. Structural performance of structure is measured in terms of the reliability index.*

The structural reliability can be applied in the design of new bridges and evaluation of existing ones. Various methods of Reliability analysis are available based on theories of probabilities and statistics. The application of reliability methods in the development of a load and resistance factor design (LRFD) bridge codes. In this paper an attempt is made to compute the reliability index for Pratt truss with post-tension member of different profiles (straight, one drape and two drape) by method of Advanced FOSM (Hasofer-Lind method), post-tensioning of truss as a technique of strengthening and rehabilitation of structurally and functionally deficit bridges. Pratt truss with post-tension member of different profiles are analyzed to compute reliability index, Load and resistance factors using MATLAB function program by Hasofer-Lind method.

***Key Words*: Pratt truss, Straight, One drape, Two drape, Reliability index, Resistance factors, Load factors, CSF.**

1. INTRODUCTION

Over the last few decades, there has been rapid increase in the volume and weight of heavy vehicles using national road networks. At the same time, more than sixty to seventy percent of bridge structures are aged over 50 years old all around the world.

The deterioration of the existing bridges due to increasing traffic volume, traffic loads, constant and continuous exposure to environmental conditions and structural ageing are becoming a major problem and those bridges are not able to cope up with current traffic requirements and forced to impose restrictions over weight, traffic and number of vehicle or strengthening of deficit structural components or even total replacement of the structure. Several methods were developed to strengthen such deficit bridges to improve the performance, due to economic constraints, historical importance and socio-political reasons, engineers looking for cost effective strengthening methods of bridges to strengthening of such bridges, of which post-tensioning is one of the popular and widely used strengthening technique due to many advantages. It is popular method of strengthening of bridges because of the (1) speed of construction, (2) minimum disruption to traffic flow, (3) easy monitoring and maintenance, (4) can be used in wide range for all span of bridges, (5) low cost involved (6) future re-stressing operation could be carried out conveniently (if required). The post tensioning of bridges has been in use since 1950's and there are many examples throughout the world, even in recent days even the post tensioning is used in many countries for the construction of new bridges and widely used in RCC bridges. For steel bridges, details available are very few and the techniques are still has no definite procedure.

The structural reliability can be applied in the analysis and design of new bridges and evaluation of existing ones. A new generation of design codes is based on probabilistic models of loads and resistance. In general, reliability-based analysis and design can be more efficient and it makes easier to achieve either to

1. Design a more reliable structure for a given cost, or

2. Design a more economical structure for a given reliability,.

Reliability can be considered as a rational evaluation criterion. It provides a good basis for the decision about repair, rehabilitation or replacement. Deterministic approach is based on analysis of individual components. A structure can be condemned, when a nominal value of load exceeds the nominal load-carrying capacity. But, in most cases, a structure is a system of components. Furthermore, when a component reaches its ultimate capacity, it is not necessarily eliminated from the structure. It continues to resist the load, but additional loads are distributed to other components. System reliability provides a methodology to establish the relationship between the reliability of an element and reliability of a system. The modern reliability analysis methods have been developed since the late 1960s. They are based on theory of probability and statistics. However, current approach to safety in the design and construction is a result of an evolution which took many centuries.

The practical applications of the reliability analysis were not possible until the pioneering work of Cornell, Lind, and Ang in the end of 1960s and early 1970s. In 1969 Cornell proposed a second-moment reliability index. Hasofer and Lind formulated a definition of format-invariant reliability index. An efficient numerical procedure was formulated for calculation of the reliability index by Rackwitz & Fiessler. Other important contributions were made by Veneziano, Rosenblueth, Esteva, Turkstra, Moses, and Ang. Their work was further improved by Der Kiuregian, Frangopol, Fujino, Furuta, Yao, Brown, Aayub, Blockley, Stubbs and Mathieu. The developed theoretical work has been presented in books as for example by Thoft-Christensen & Baker, Augusti, Baratta & Ciascati, Madsen et al.. Ang & Tang, Melchers, and Thoft-Christensen & Murotsu.

By the end of 1970s, the reliability methods reached a degree of maturity and they are now available for applications. In the coming years, one can expect a further acceleration in the development of analytical methods to model the behavior of structural systems. The real change can be expected by focusing on structural systems. The reliability analysis will also be applied to structural systems.

2. OBJECTIVE

Objective of this paper is to analyze the pratt truss without and with post-tensioning members of different layouts to compute reliability index, Load factor, resistance factor and central safety factors. It require to achieve the objective, the development of Limit State Function are defined as mathematical formulas describing the state (safe or failure). Structural performance can be measured in terms of the reliability or probability of failure. Reliability can be measured in terms of the reliability index and is calculated using an iterative procedure using Hasofer Lind method by using MATLAB program.

3. PRESENT STUDY

3.1 Pratt truss with post tension member with different layouts

The present study, a truss bridge of 64 m long, 13 m wide desk slab with two lane carriage way of 6.80 m having foot path of 1.50 m either side, supported by pratt type truss girder on either side, having 16 panels of 4m each with an height of 8 m consists of top chord members, bottom chord members, diagonal and vertical members proposed to carry standard IRC class A wheeled vehicle loading. The Pratt truss without post tensioning member is a perfect determinate truss with 32 joint and 61 members satisfying m=2j-3, with the introduction of post tension member of different profiles as measure of strengthening creates redundancy and the determinate truss become indeterminate. Fig -1 shows the pratt truss without and with post-tensioned members of different profiles.

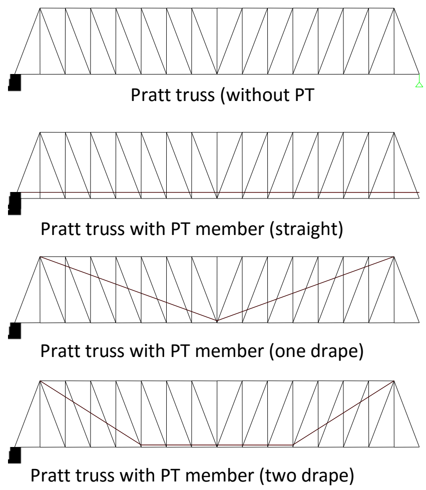

Fig. 1 Pratt truss without and with PT members (Straight, One drape and Two drape)

Fig -1: Pratt truss without and with PT members (Straight, One drape and Two drape)

The details of geometrical and material constants static analysis to compute axial forces in members of pratt truss considered for study with post-tension member of different profiles (straight, one drape and two drape) members are as details are tabulated below in Table -1.

Table -1: Details of Pratt truss

Members		Length m	Area m²	Young's Modulus .kN/m2	R_{gy} mm
Top Chord	32 to 45	4.00	0.0458709	2.00E+08	104.07
Bottom Chord	46 to 61	4.00	0.0534838	2.00E+08	101.14
Diagonal Member	1,3,..to 31	8.94	0.0441935	2.00E+08	96.64
Vertical Member	2, 4 ..to 30	8.00	0.0275483	2.00E+08	92.01
PT Member (Straight)	62	64.00	0.0101616	1.60E+08	28.43
PT Member (One drape)	62	58.24	0.0101616	1.60E+08	28.43
PT Member (Two drape)	62	59.77	0.0101616	1.60E+08	28.43

3.2 Load and Resistance considerations

Dead load is the gravity load due to the self-weight of the structural and non-structural elements permanently connected to the bridge. All components of dead load can be treated as normal random variables. Live load covers a range of forces produced by vehicles moving on the bridge. The effect of live load depends on many parameters including the span length, truck weight, axle loads, axle configuration, position of the vehicle on the bridge (transverse and longitudinal), number of vehicles on the bridge (multiple presence), girder spacing, and stiffness of structural members (slab and girders). Bridge live load is strongly site-specific. The variation is not only from country to country, but within a region, depending on local traffic volume and mix, legal load limits, and special conditions. Therefore, the statistical parameters can also be site-specific.

Present study, dead load's contributed are self-weight of (a) 250mm thick RCC deck slab including wearing coat, (b) Foot path of 1.50m wide on either side of carriage way, (c) Hand railing's in foot path, (d) Cross girder between truss joints supporting deck slab and (e) pratt truss. The live load considered is the two lane vehicular load of IRC Class A wheeled vehicle.

The causes of uncertainty about the structural resistance depends on the property of material: Strength of material, modulus of elasticity and chemical composition etc,. The static analysis carried using direct stiffness method to compute tensile and compressive forces in members of Pratt truss with post-tension member of different layouts (straight, one drape and two drape) using function program in MATLAB. The result of axial forces in members for different truss configurations are presented in Table -2. and are utilised as input for reliability analysis using Hasofer and Lind's Method to compute the reliability index, Load factor, resistance factor and central safety factors of pratt truss with different layouts of post tension member as a measure of strengthening.

Table -2: Forces in members with their ratio with respect to Pratt truss (1+0)

Member	Forces kN	Forces kN	Ratio	Forces kN	Ratio	Forces kN	Ratio
	1+0	1+1	1+1/ 1+0	1+2	1+2/ 1+0	1+3	1+3/ 1+0
1	3295.41	3295.41	1.00	3321.38	1.01	3322.06	1.01
2	-393.00	-393.00	1.00	-393.00	1.00	-393.00	1.00
3	-2856.02	-2856.02	1.00	-1516.24	0.53	**473.21**	**-0.17**
4	2161.50	2161.50	1.00	963.17	0.45	**-816.25**	**-0.38**
5	-2416.63	-2416.63	1.00	-1076.86	0.45	**912.60**	**-0.38**
6	1768.50	1768.50	1.00	570.17	0.32	**-1209.25**	**-0.68**
7	-1977.24	-1977.24	1.00	-637.47	0.32	**1351.99**	**-0.68**
8	1375.50	1375.50	1.00	177.17	0.13	**-1602.25**	**-1.16**
9	-1537.86	-1537.86	1.00	-198.08	0.13	**1791.38**	**-1.16**
10	982.50	982.50	1.00	**-215.83**	**-0.22**	982.50	1.00
11	-1098.47	-1098.47	1.00	**241.31**	**-0.22**	-1098.47	1.00
12	589.50	589.50	1.00	**-608.83**	**-1.03**	589.50	1.00
13	-659.08	-659.08	1.00	**680.69**	**-1.03**	-659.08	1.00
14	196.50	196.50	1.00	**-1001.83**	**-5.10**	196.50	1.00
15	-219.69	-219.69	1.00	**1120.08**	**-5.10**	-219.69	1.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	-219.69	-219.69	1.00	**1120.08**	**-5.10**	-219.69	1.00
18	196.50	196.50	1.00	**-1001.83**	**-5.10**	196.50	1.00
19	-659.08	-659.08	1.00	**680.69**	**-1.03**	-659.08	1.00
20	589.50	589.50	1.00	**-608.83**	**-1.03**	589.50	1.00
21	-1098.47	-1098.47	1.00	**241.31**	**-0.22**	-1098.47	1.00
22	982.50	982.50	1.00	**-215.83**	**-0.22**	982.50	1.00
23	-1537.86	-1537.86	1.00	-198.08	0.13	**1791.37**	**-1.16**
24	1375.50	1375.50	1.00	177.17	0.13	**-1602.25**	**-1.16**
25	-1977.24	-1977.24	1.00	-637.47	0.32	**1351.98**	**-0.68**
26	1768.50	1768.50	1.00	570.17	0.32	**-1209.25**	**-0.68**
27	-2416.63	-2416.63	1.00	-1076.86	0.45	**912.60**	**-0.38**
28	2161.50	2161.50	1.00	963.17	0.45	**-816.25**	**-0.38**
29	-2856.02	-2856.02	1.00	-1516.24	0.53	**473.21**	**-0.16**
30	-393.00	-393.00	1.00	-393.00	1.00	-393.00	1.00
31	3295.41	3295.41	1.00	3321.38	1.01	3322.06	1.01
32	2751.00	2751.00	1.00	6398.26	2.33	7262.97	2.64
33	3831.75	3831.75	1.00	6879.84	1.80	6854.84	1.79
34	4716.00	4716.00	1.00	7164.93	1.52	6250.21	1.33
35	5403.75	5403.75	1.00	7253.51	1.34	5449.09	1.01
36	5895.00	5895.00	1.00	7145.60	1.21	5940.34	1.01
37	6189.75	6189.75	1.00	6841.18	1.11	6235.09	1.01
38	6288.00	6288.00	1.00	6340.27	1.01	6333.34	1.01
39	6288.00	6288.00	1.00	6340.27	1.01	6333.34	1.01
40	6189.75	6189.75	1.00	6841.18	1.11	6235.09	1.01
41	5895.00	5895.00	1.00	7145.60	1.21	5940.34	1.01
42	5403.75	5403.75	1.00	7253.51	1.34	5449.09	1.01
43	4716.00	4716.00	1.00	7164.93	1.52	6250.21	1.33
44	3831.75	3831.75	1.00	6879.84	1.80	6854.84	1.79
45	2751.00	2751.00	1.00	6398.26	2.33	7262.97	2.64
46	-1473.75	**2487.24**	**-1.69**	-1485.36	1.01	-1485.67	1.01
47	-1473.75	**2487.24**	**-1.69**	-1485.36	1.01	-1485.67	1.01

48	-2751.00	**1209.99**	**-0.44**	-2163.45	0.79	-1274.04	0.46
49	-3831.75	**129.24**	**-0.03**	-2645.03	0.69	-865.92	0.23
50	-4716.00	-755.01	0.16	-2930.12	0.62	-261.29	0.06
51	-5403.75	-1442.76	0.27	-3018.70	0.56	**1722.86**	**-0.32**
52	-5895.00	-1934.01	0.33	-2910.79	0.49	**1231.61**	**-0.21**
53	-6189.75	-2228.76	0.36	-2606.37	0.42	**936.86**	**-0.15**
54	-6189.75	-2228.76	0.36	-2606.37	0.42	**936.86**	**-0.15**
55	-5895.00	-1934.01	0.33	-2910.79	0.49	**1231.61**	**-0.21**
56	-5403.75	-1442.76	0.27	-3018.70	0.56	**1722.86**	**-0.32**
57	-4716.00	-755.01	0.16	-2930.12	0.62	-261.29	0.06
58	-3831.75	**129.24**	**-0.03**	-2645.03	0.69	-865.92	0.23
59	-2751.00	**1209.99**	**-0.44**	-2163.45	0.79	-1274.05	0.46
60	-1473.75	**2487.24**	**-1.69**	-1485.37	1.01	-1485.67	1.01
61	-1473.75	**2487.24**	**-1.69**	-1485.37	1.01	-1485.67	1.01
Compression " +ve " , Tension " -ve " Ratio of forces wrt (1+0) > 1 increase , < 1 decrease							
Bold figures indicates : Change in nature of forces in members w.r.t (1+0)							

3.3 Hasofer and Lind's Method

Problem of computing minimum value of reliability index (β) for a non-linear failure surface is solved iteratively using by Hasofer and Lind's method and the basic variables (Xi) are defined as normalized variables (Zi) in an transformed or reduced coordinates. Hasofer and Lind's method defines the Reliability index (β) as, it is the shortest distance from the origin O to the failure surface in normalized coordinate system. The Hasofer-Lind method is applicable for normal random variables.

An algorithm to compute β by Hasofer-Lind method as follows

1. Define the appropriate limit state equation.

   g(x)= (x1, x2 , ……….xn) =0

2. Normalize the basic variables using

$$z_i = \frac{X_i - \mu_i}{\sigma_i}, \qquad i = 1,2, \dots \dots \quad n$$

3. Write the Limit State Failure surface equation in terms normalized that is g1 (z1, z2, …. zn) = 0 and evaluate

$$\left[\frac{\partial g_i}{\partial Z_i}\right] \quad i = 1,2, \dots \dots . n$$

at design point zi = αi β , and write gi (z) in terms of β and αi , such that $\beta = g(\beta, \alpha_1, \alpha_2, \dots\dots \alpha_n)$ for computation of β.

4. Select a value of β and values of $(\alpha_1, \alpha_2, \dots\dots \alpha_n)$ satisfying $\sum \alpha_i^2 = 1$, choosing positive values of α_i for load variables and negative values for resistance variables.

5. Start the iteration; calculate the new value of β using the equation $\beta = g(\beta, \alpha_1, \alpha_2, \dots\dots \alpha_n)$.

6. Calculate the value of

$$K = [\textstyle\sum_1^n \left(\frac{\partial g_i}{\partial z_i}\right) \alpha_i^2]^{1/2} = 1,$$

7. Determine new value of α_i, using

$$\alpha_i = \frac{1}{K}\left(\frac{\partial g_i}{\partial z_i}\right) \qquad i = 1, 2, \dots \dots \quad n$$

8. With new values of β and α, start the next iteration, and repeat from step 5 through 6, until β converges.

Using MATLAB, a function program is developed for analysis of pratt truss to compute the Reliability index (β) of pratt truss with post-tension members of different profiles consists of both tension and compression members, using

Limit State Function given by equation, for compression (for buckling) members:

$$g(x) = \frac{\Pi^2 AER_{gy}^2}{L^2} - Fc \ ,$$

and for tension members :

$$g(x) = f_y A - F_T \ ,$$

where, fy , A, E, Rgy, L, FT and FC are characteristic values of basic variables Yield strength of steel in N/mm2, Area of cross section of members in mm2 , Modulus of steel in N/mm2, Minimum Radius of gyration in mm, Length of members in mm, Axial force in tension and compression member in kN respectively. The values of basic variables and the forces in members from static analysis along with values of Coefficient of Variation (CoV) of 0.05 for resistance (basic) variable fy , A, E, Rgy, L, and values of Coefficient of Variance (CoV) of 0.20 for Load (basic) variables (dead load and live load) with normal distribution are considered for reliability analysis.

The Reliability analysis is carried out, to compute reliability index, Load and resistance factors for tension members and compression members of Pratt truss with post-tension member of different profiles (straight, one drape and two drape) using function program in MATLAB as per algorithm for Hasofer-Lind method. The advantage of Hasofer-Lind method , if any error in computations automatically get self -corrected by increasing the number of iterations till values converged.

The results of reliability analysis, i.e. the mean values of reliability index (β) , Resistance Factor (Φ) , Load Factor (ɣ) and Central Safety Factors (CSF) for diagonal members, vertical members, top chord members and bottom chord members in pratt truss are presented in Table -3 and Table -4, for discussion.

Table -3: Mean Values of Reliability Index (βHL) & CSF

Members	Beta (βHL)	Resistance Factor (Φ_R)	Load Factor (γ_L)	CSF
Pratt truss without post tension member (1+0)				
Diagonal	16.0861	0.4075	3.6835	9.3274
Vertical	13.2511	0.3831	5.5113	15.2330
Top Chord	13.4376	0.3660	7.5890	21.0894
Bottom Chord	11.1903	0.5542	3.8198	7.9321
Pratt truss with Post tension member (Straight) (1+0)				
Diagonal	15.4735	0.4075	3.6840	9.3292
Vertical	12.9520	0.3830	5.5132	15.2398
Top Chord	13.4376	0.3660	7.5890	21.0894
Bottom Chord	16.6743	0.3252	8.2492	27.8321
Pratt truss with Post tension member (One drape) (1+2)				
Diagonal	15.8410	0.3661	5.5285	16.7356
Vertical	16.8089	0.3208	5.3162	16.4839
Top Chord	11.8153	0.4230	5.9440	14.5254
Bottom Chord	14.2865	0.4304	4.5737	10.8890
Pratt truss with Post tension member (Two drape) (1+3)				
Diagonal	14.4847	0.3900	4.9552	13.5721
Vertical	14.4847	0.3432	5.7216	16.7505
Top Chord	12.9379	0.3791	6.9731	18.4326
Bottom Chord	17.7927	0.3103	7.1083	24.1624

Table -4: Mean values of Reliability Index

Members	Reliability Index (β_{HL})			
	(1+0)	(1+1)	(1+2)	(1+3)
Diagonal	16.086117	15.473550	15.840997	14.612345
Vertical	11.241415	12.088559	15.688334	14.484714
Top Chord	13.437568	13.437568	11.815287	12.937879
Bottom Chord	11.190342	16.674284	14.286534	17.792671
All Members	12.988860	14.418490	14.407788	14.956902

Table -5: Mean values of Central Safety Factors and their Ratio's.

Members	Central Safety Factor(CSF)			
	(1+0)	(1+1)	(1+2)	(1+3)
Diagonal	9.3274	9.3292	16.7356	13.5721
Vertical	15.2330	15.2398	16.4839	16.7505
Top Chord	21.0894	21.0894	14.5254	18.4326
Bottom Chord	7.9321	27.8321	10.8890	24.1624
All Members	**13.395475**	**18.372623**	**14.658468**	**18.229388**

4. RESULTS AND DISCUSSION

The reliability analysis of pratt truss without and with three different layout of post tension member as shown in Fig -1, the member properties are presented in Table -1 for the member axial tensile (F_T) and compressive(F_C) forces presented in Table -2, obtained by static analysis are utilised as Load (basic) variables as input to function program in MATLAB as per algorithm for Hasofer-Lind method for Limit State Function given by equation, for compression (for buckling) members $g(x) = \frac{\Pi^2 AER_{gy}^2}{L^2} - Fc$, and for tension members $g(x) = f_y - F_T$, The reliability analysis results

(a) The Mean values of Reliability Index (βHL) and Central Safety Factors along with Resistance factor (Φ_R) and Load factor (γ_L) are presented in Table -3,

(b) The Mean values of Reliability Index are presented in Table 4 and

(c) The mean values of Central Safety Factors are presented in Table -5 for members in pratt truss with different layout of post tension member.

4.1 Reliability index (Table -4):

It is observed that there is increase in the value of reliability index (β_{HL}) with the introduction of post tensioned members with different layout i.e. straight , one drape and two drape are presented below:

The LRFD format for diagonal members
0.4075 Rm⩾3.68 Sm (for straight)
0.3661 Rm⩾3.5285 Sm (for One drape)
0.3900 Rm⩾4.9552 Sm (for Two drape)

The LRFD format for vertical members
0.3839 Rm⩾3.3132 Sm (for straight)
0.3208 Rm⩾5.3162 Sm (for One drape)
0.3432 Rm⩾5.7216 Sm (for Two drape)

The LRFD format for top chord members
0.3660 Rm⩾7.5890 Sm (for straight)
0.4230 Rm⩾4.944 Sm (for One drape)
0.3191 Rm⩾6.9731 Sm (for Two drape)

The LRFD format for bottom chord members
0.3252 Rm⩾8.2492 Sm (for straight)
0.4314 Rm⩾4.5737 Sm (for One drape)
0.3163 Rm⩾7.1083 Sm (for Two drape)
as calibrated by IS 800-2007 code of practice.

4.2 Central Safety Factors (Table -5):

The central safety factor is multiplication of resistance factor and load factor and it is useful for engineers, who are not familiar with LRFD format.

5. CONCLUSION :

(1). One problem with this approach is that the engineering community is not comfortable in using reliability index. This is due to the difficulty in appreciating the probability of failure (P_f). They are not absolute values and it should be compared with target values.
(2). Introduction of post-tension cable of different layout in a pratt truss, the member forces and joint displacements are reduced.
(3). Having computed the reliability of elements and it is compared with the acceptable target reliability for the failure mode and if the computed reliabilities is lower than the target reliability and it is reasonable to conclude that the structure is less safe, conversely if the computed reliability is above the target reliability, then the structure is safe.

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