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ANALYSIS AND DESIGN OF CABLE-STAYED BRIDGE

Gurajapu Naga Raju[1], J. Sudha Mani[2]
[1]M. Tech Student, [2]Internal Guide,
Department of civil engineering, USHARAMA COLLEGE OF ENGINEERING & TECHNOLOGY
(NAAC "A" grade, Approved by A.I.C.T.E, Affiliated to J.N.T.U. Kakinada),TELAPROLU -521109,AP

Abstract: This project report is all about the analysis of the cable-stayed bridges for attaining the cable forces, girder moments and shear forces of the girder and the pylons. The methods adopted for attaining the cable forces is the strain energy principle. This strain energy principle was adopted from a journal of ASCE and the same procedure is followed from that journal. This journal was incorporated with some assumptions. The same assumptions were considered for making this report. The obtained cable forces which are done by strain energy principle are cross checked with the STAAD results. As the strain energy principle is a procedure which comprises of a laborious iterative process, a "C" programming is made for this procedure, which performs the analysis according to our requirement of the no. of cables, girder span, pier portion, loading conditions, tower dimensions, stiffness of all elements, position of cables. Thus, the difference between these values of the cable forces obtained from the strain energy method and that obtained from the STAAD gave not much difference, the STAAD Pro analysis is performed for the model chosen for designing.The model chosen for designing is performed for analysis and later on, carried out with designing of the pylon dimensions, steel girder and the deck slab along with the concrete pylon.
Keywords: Strain-Energy, Pylon- Cables-Cable Forces-C Programming- longitudinal, cross girder, deck slab-STAAD Pro.

I. INTRODUCTION

Cable stayed bridges have good stability, optimum use of structural materials, aesthetic, relatively low design and maintenance costs, and efficient structural characteristics. Therefore, this type of bridges are becoming more and more popular and are usually preferred for long span crossings compared to suspension bridges

Fig:1.1 A Typical Cable Stayed Bridge

A typical cable stayed bridge is a deck with one or two pylons erected above the piers in the middle of the span. The cables are attached diagonally to the girder to provide additional supports. A typical cable-stayed bridge is depicted in Fig. 1.1**.** The pylons form the primary load-bearing structure in these types of bridges. Large amounts of compression forces are transferred from the deck to the cables to the pylons and into the foundation as shown in Fig. 1.2.

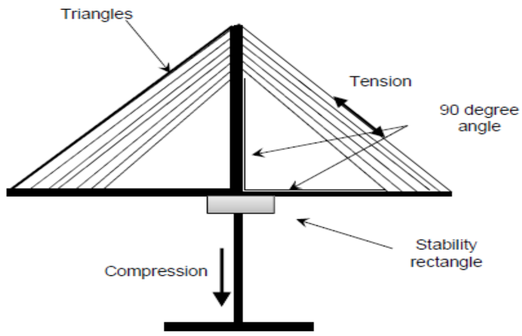

Figure 1.2: Illustration of Typical Cable-Stayed Bridge.

1.1 Deck:

The deck or road bed is the roadway surface of a cable-stayed bridge. The deck can be made of different materials such as steel, concrete or composite steel-concrete. The choice of material for the bridge deck determines the overall cost of the construction of cable stayed bridges. The weight of the deck has significant impact on the required stay cables, pylons, and foundations (Bernard et al., 1988). As one can see in Fig. 1.3, the composite steel-concrete deck is composed of two structural edge girders. These girders are attached by transverse steel floor beams. The precast reinforced concrete deck is supported by these two main girders.

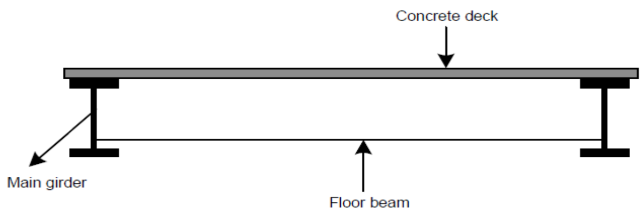

Figure 1.3: Composite Deck

1.2 Pylons:

Pylons of cable stayed bridges are aimed to support the weight and live load acting on the structure. There are several different shapes of pylons for cable stayed bridges such as Trapezoidal pylon, Twin pylon, A-frame pylon, and Single pylon. They are chosen based on the structure of the cable stayed bridge (for different cable arrangements), aesthetics, length, and other environmental parameters.

1.3 Cables:

Cables are one of the main parts of a cable-stayed bridge.

They transfer the dead weight of the deck to the pylons. These cable are usually post-tensioned based on the weight of the deck. The cables post-tensioned forces are selected in a way to minimize both the vertical deflection of the deck and lateral deflection of the pylons.

1.4 Pylon Principle:

In principle the pylon is a tower structure where the most decisive load will be the axial force originating from the vertical components of the forces in the cables attached to the pylon. The pylon has to carry heavy loads, usually several thousands of tons. Therefore, box sections with a large kern width are the best to provide safety against buckling with the minimum amount of material.

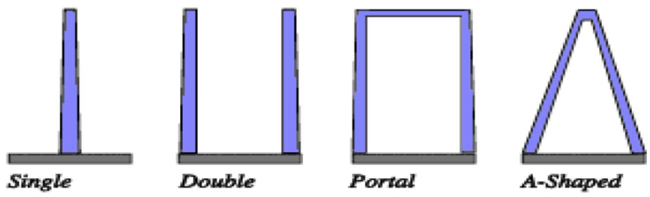

Fig:1.5 Types of Commonly Used Bridge Towers.

1.5 Methods of Analysis for Attaining the Cable Forces:
1) Non-linear analysis of cable – stayed bridges
2) Linear analysis of cable stayed bridges
3) STAAD Analysis using STAAD Pro software
4) Strain energy method of analysis

II. STRAIN ENERGY METHOD

The method adopted by us is the strain energy method which was adopted from a journal from ASCE named "Energy Analysis Of Cable-Stayed Bridges" by Hassan I. A. Hegab1

2.1 Method of analysis

Consider the system shown in Fig.2. 1 where the stay cables 1, 2, ...,*N*can be replaced by a system of elastic supports with stiffnesses$k_1, k_2, \ldots, k_N$. Ifthe support provided by the pier is released, the loaded girder may thus be reduced to the base system shown in Fig. *2(a).* Now, the potential energy *U* for the girder base system can be expressed as

$$u = \int_0^L \int_0^K MdKdx - \int_0^L \int_0^y pdxdy + \sum_{i=1}^{N} \int_0^{y_i} W_i dy_i$$

$$= EI_G \int_0^L \int_0^{y^{11}} y^{11} dy^{11} dx - \int_0^L \int_0^y pdxdy + \sum_{i=1}^{N} \int_0^{y_i} W_i dy_i \ldots\ldots\ldots\ldots (1)$$

in which M = EI_G-y'' = bending moment in the girder; $K = y''$ = d^2y/dx^2 = curvature of the girder; EI_G = its bending stiffness; L = span length(between the two end abutments); *y* = vertical deflection of the girderat a point distance *x* from the left end support; $W_i = F_i \sin 0_i$ = vertical component of the axial force F_i in cable *i* due to the application of the live load *p*on the girder; θ_i = slope of cable i (to the horizontal); y_i =girder deflection at a point distance x_i from the left end abutment, where cable *i* is anchored to the girder; and *N* = totalnumber of stay cables. The girder deflection y at any point distance x from the left end abutment**,** fig. 2.2(a), may be expressed as

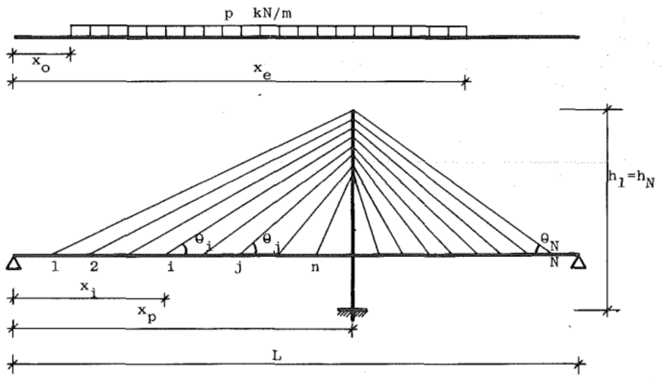

Fig.2.1 Bridge Configuration and Live Load

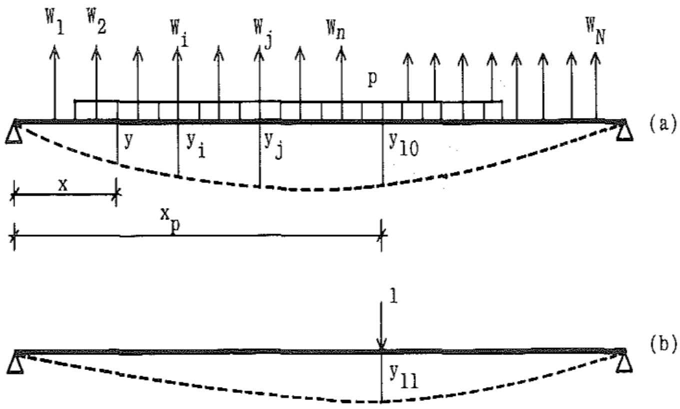

Fig.2.2 Base System of The Girder. (a) Deflection Curve Due to Live Load and Cable Forces, And (b) Deflection Curve Due to Unit Girder Reaction at Pier Support

$y = \sum_{j=1}^{\infty} a_j \sin\frac{j\pi x}{L}$.................. (2)

In which a_j= Fourier coefficient. For a stationary potential energy, $\partial U/\partial a_m = 0$, and thus, one can write

$$EI_G.\int_0^L y^{11}\frac{\partial y^{11}}{\partial a_m}dx - \int_0^L p\frac{\partial y}{\partial a_m}dx + \sum_{i=1}^{N} W_i\frac{\partial y_i}{\partial a_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In which,$y^{11} = -\sum_{j=1}^{\infty}\left(\frac{j\pi}{L}\right)^2 a_j \sin\frac{j\pi x}{L}$; $\frac{\partial y^{11}}{\partial a_m} = -\left(\frac{m\pi}{L}\right)^2 \sin\frac{m\pi x}{L}$; $\frac{\partial y}{\partial a_m} = \sin\frac{m\pi x}{L}$; *and* $\frac{\partial y_i}{\partial a_m} = \sin\frac{m\pi x_i}{L}$....... (4)

For a uniform live load p extending from $x_0$to x_e, Fig. 1.1, a Fourier coefficient a_m can be obtained by substitution from Eqs. 4 into Eq. 3, and after manipulation, as

$$a_m = \frac{\left(\frac{p.L}{m\pi}\right).\left[\cos\frac{m\pi x_0}{L} - \cos\frac{m\pi x_e}{L}\right] - \sum_{i=1}^{N} W_i \sin\frac{m\pi x_i}{L}}{EI_G.\left(\frac{m\pi}{L}\right)^4.\frac{L}{2}} \ldots\ldots (5)$$

Using Eq. 5, the deflection curve, Fig. *2(a),* can be obtained if the vertical components W_i of the cable forces F_i are known. However, the cable forces F_i are not known and an iterative procedure should be developed in order to solve the problem.

The girder deflection y_{10} at the pier point for the base system, Fig. 2.*2(a),* can thus be written in the form

$y_{10} = \sum_{j=1}^{\infty} a_j \sin\frac{j\pi x_p}{L}$............(6)

in which x_p= horizontal distance from the pier to the left support. Similarly, a Fourier coefficient $b_m$for the deflection curve due to unit girder reaction at the pier position, Fig. *2.2(b),* can be obtained as

$$b_m = \frac{\sin\frac{m\pi\, x_p}{L}}{EI_G.\left(\frac{m\pi}{L}\right)^4 \frac{L}{2}} \text{……….(7)}$$

The girder deflection y_{11} at the pier point due to unit girder reaction at the pier position, Fig. *2.2(b),* may thus be written as

$$y_{11} = \sum_{j=1}^{\infty} b_j \sin\frac{j\pi\, x_p}{L} \text{…………(8)}$$

Thus, the girder reaction R_1at the pier support can be obtained, using Eqs. 6 and 8, as

$$R_1 = \frac{-y_{10}}{y_{11}} \text{……(9)}$$

The final deflection Y of the girder, fig.1, becomes

$$Y = \sum_{j=1}^{\infty} a_j \sin\frac{j\pi x}{L} + R_1.\sum_{j=1}^{\infty} b_j.\sin\frac{j\pi x}{L} \text{…….(10)}$$

The final value of the tension F_i in cable i, Fig.3, is given by

$$F_i = k_i(Y_i \sin\theta_i \pm \Delta_i \cos\theta_i) \text{…….(11)}$$

in which f_c, = stiffness of cable *i;* A, = horizontal displacement of the pylon at the point of attachment of cable *i;* Y_i = final girder deflection at the point where cable *i* is anchored; and *i* = 1, 2, ..., *N.*

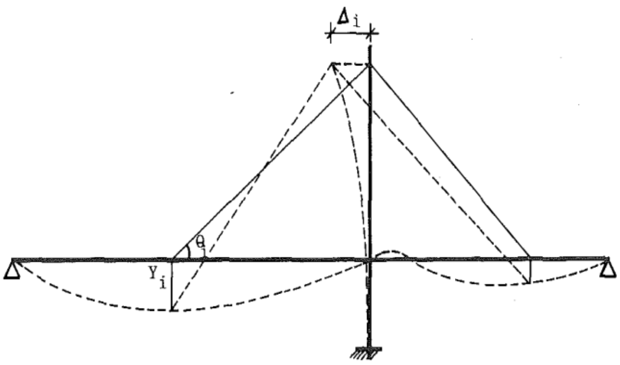

Fig:2.3 Final Movements of Two Ends of Cable i

Thus, the vertical and horizontal components W_i, and Q_i of the cable tension F_i are given by

$$W_i = F_i \sin\theta_i \text{……….(12a)}$$

$$Q_i = F_i \cos\theta_i \text{……….(12b)}$$

Again, W_i and Q_i are determined in terms of the vertical deflection Y_i of the girder and the horizontal displacement A, of the pylon, see Eq.11.

The procedure for solving the problem can be summarized as follows:

1. Eq. 8 is used to find the girder flexibility coefficient *yu*for the pier point, Fig. *2.2(b).*
2. Guess some initial values for the cable tensions F_i, e.g., F_i = 0.
3. The horizontal components Q, of the cable tensions F_i are determined from Eq. 12(b). Then, using Eq. 19, the horizontal displacements Δ_i, of the pylon can be determined, see below.
4. Using Eq. 12(a), the vertical components W_i of the cable tensions F_i are determined.
5. The Fourier coefficients $a_m$are then determined using Eq. 5.
6. The girder deflection y_{10} at the pier point for the base system**,** Fig. 2.2(a), can be determined using Eq. 6.
7. Eq. 9 is then used to determine the girder reaction R_1at the pier support.
8. The final girder deflections V, are then obtained using Eq. 10.
9. Improved values for the cable tensions F; can then be obtained using Eq. 11.
10. Steps 3 through 9 are repeated until convergence is obtained. Convergence may be achieved if the difference in the value of the tension F_i in any cable *i*, determined from two successive iterations, does not exceed a small percentage (say 1%).

The axial compressive force in the pylon F_p, due to live load, is equal to the sum of the vertical components W_i of the forces F_i in all cables attached to the pylon, i.e.

$$F_P = \sum_{i=1}^{N} W_i \text{……….(13)}$$

The axial compressive load in the pier *Rp*, due to live load, is equal to the axial force in the pylon *Fp*plus the girder reaction *Ri*at the pier position, i.e.

$$R_P = F_P + R_1 \text{……….(14)}$$

2.2 Numerical Example:

Consider a 600m span single towered cable stayed bridge to analyse for the cable forces in the above mentioned strain energy iterative process. As the procedure comprises of number of iterations, a C Program has been written for the whole procedure.

The considered loading condition and the type of bridge is shown in thefig.2.5 below.

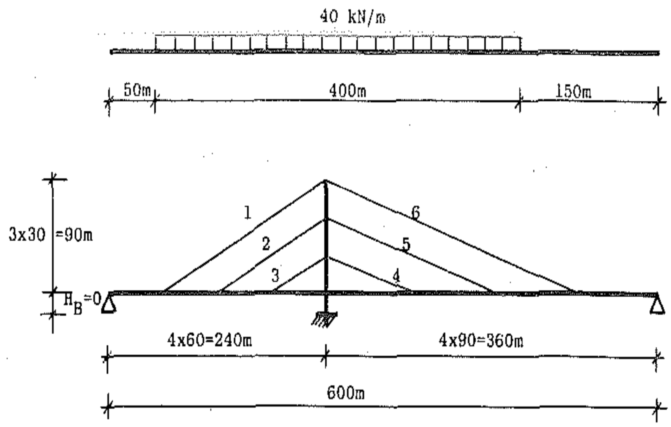

Fig. 2.5 Span Bridge with Dimensions and Live Load

2.3 Results from C Program:

The results obtained from this program for the given system as shown in fig.2.7 are shown below.

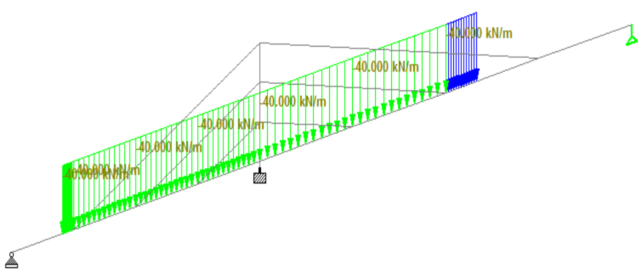

Fig.2.7 Sample Cable Stayed Bridge Considered for Comparing with STAAD

a_1 = 12.502844, a_2 = 0.344432, a_3 = -0.010816,
a_4 = 0.012994, a_5 = -0.001406, a_6 = 0.000112,
a_7 = 0.000261, a_8 = -0.000427, a_9 = 0.000013

b_1 = 0.001054, b_2 = 0.000041, b_3 = -0.000008, b_4 = -0.000004, b_5 =0, b_6 = 0.000001,
b_7 =0, b_8 =0, b_9 =0

R = 11660.814228 KN
Δ_1= -0.1285, Δ_2 = -0.069315, Δ_3 = -0.02081,
Δ_4 = 0.02081, Δ_5 = 0.069315, Δ_6 = 0.1285
Y_1= 0.101163, Y_2 = 0.118109, Y_3 = 0.041959,
Y_4 = 0.216196, Y_5 = 0.348233, Y_6 = 0.225001
F_1 = 1010 kN, F_2 = 2460 kN, F_3 = 2200 kN,
F_4 = 3570 kN, F_5 = 3050 kN, F_6 = 300 kN

III. RESULTS FOR LONGITUDINAL GIRDER FROM STAAD PRO ANALYSIS

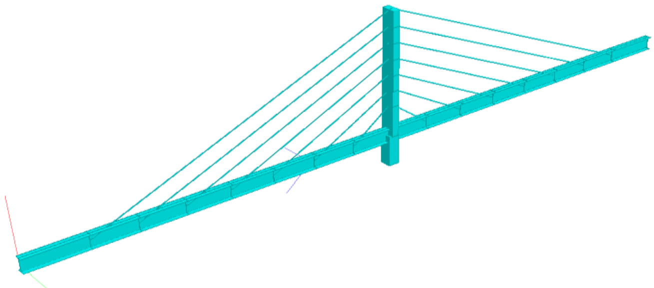

Fig:3.1 Model of Cable Stayed Bridge

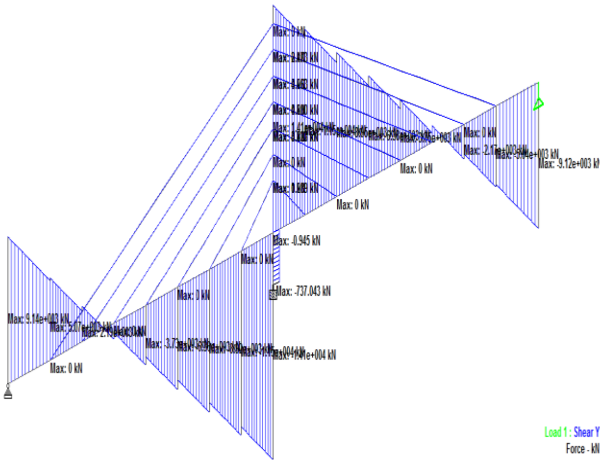

Fig:3.4 Shear Force for Longitudinal Girder

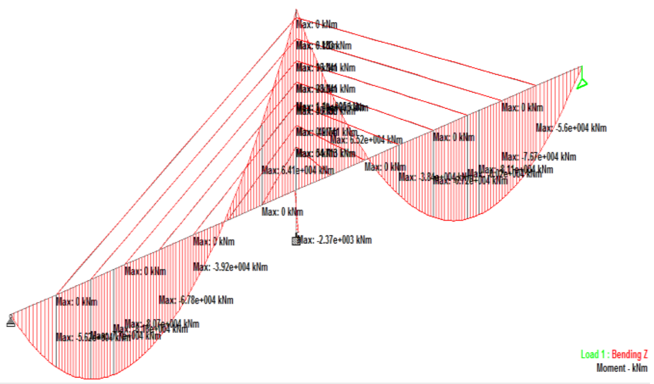

Fig:3.5 Bending Moment of Cable Stayed Bridge

IV. DESIGN

4.1 Design of Interior Slab Panel:
Here the considered slab panel is assumed to be simply supported on all the four sides. The clear dimensions of the slab panel here is 1.2m X 2.7m
Assume thickness of slab= 350mm
Assume thickness of wearing coat= 80mm

4.1.1 Class-AA Tracked Vehicle:
Tail to nose distance > 90m (class-AA tracked vehicle)
Clearance = 0.3m for single lane
Spacing of two axles $\leq$ 1.2m

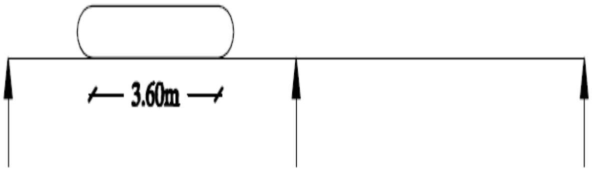

Fig:4.1 Tracked Vehicle for Class AA Loading
$M_1 = (m_1 + 0.15 m_2)$P = 15.19kNm
$M_2 = (m_2 + 0.15 m_1)$P = 4.57kNm

4.1.2 Reinforcement and Section:
$\sigma_{cbc} = 8.3$, $\sigma_{st} = 200$, j = 0.9. q = 1.1, K = 0.314
d= $\sqrt{\frac{M}{Q.b}} = \sqrt{\frac{16.29\times10^6}{1.1\times1000}}$= 121.69 ≤169mm, hence safe.
D = 215, d = 215-40 –(12/2) = 169mm
Minimum reinforcement =$\frac{0.12}{100}(1000 \times 215) = 258 mm^2$
Provide 10φ @ 300 c/c

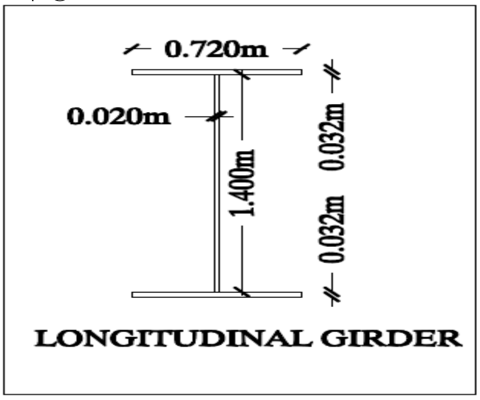

Fig:4.14 Longitudinal Girder Dimensions Designed

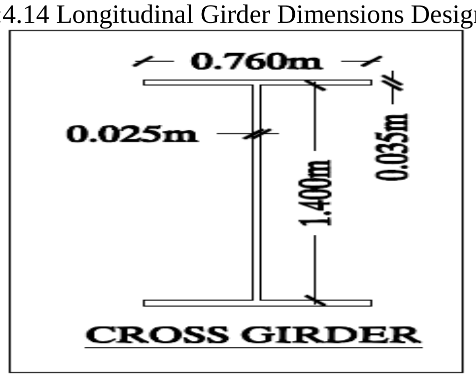

Fig:4.15 Cross Section of the Cross Girder Designed

4.1.3 Pylon Design:
Design Moments and Axial Forces are obtained from STAAD analysis considering dead load on full span and live load is applied on one side of the pylon and wind load is also considered which is assumed to be acting at mid height of the pylon.

4.2. Wind Load Calculations:
As per Clause IS:875 (part-3) 1987 from page 8,
Terrain Category-1,
As per Clause IS:875 (part-3) 1987 from page 11,
Class-BFrom Table-1,Cl: 5.3.1 K_1 = 1.08 for 100 years.
From Table-1,pg-12
K_2 = 1.13 for 30 m height and K_3 = 1
In Visakhapatnam zone , Wind speed = 50 m/sec
$V_Z = V_b K_1 K_2 K_3$
$= 50\times1.08\times1.13\times1 = 61.02$ m/sec
Design wind speed = 61.02 m/sec
As per Clause :5.4, IS:875 (part-3) 1987 ,
$p_z = 0.6 \times V_Z^2 = 0.6 \times 61.02^2 = 2234.06$ N/m^2= 2.234kN/m^2

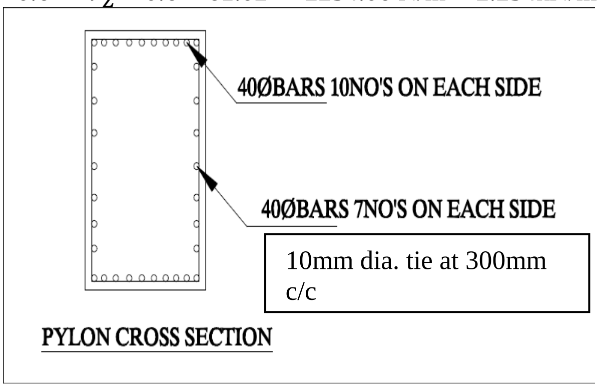

Fig:4.16 Cross Section of the Pylon

V. CONCLUSION

- In this project with the help of journals based on Strain Energy we have done 'C' programming, STAAD analysis and from this the results of the analysis were compared with the manual calculations and we opted STAAD analysis because the obtained cable forces were more than the results obtained from the strain energy analysis for designing on a safer side.
- Using STAAD Pro. software results the design is done manually
- For the future scope of the project, we have done with concrete pylons and for extension of project anyone can continue the thesis with steel pylons and compare the results and economy of the project.
- Girder which is designed using steel could also be replaced by concrete girder and compare the results and economy of the project.

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