DEVELOPMENT OF A SOFTWARE FOR ANALYSIS AND DESIGN OF SUSPENSION BRIDGES

Ranjan Abraham*

Abstract:

This work deals with the development of a computer application for the analysis and design of suspension bridges. The purpose of the following work is to provide a general introduction to suspension bridges and a discussion of structural response of various components of suspension bridge. The present work highlights the methodologies used in the development of the software for suspension bridges. The package developed is intended to improve the user friendliness for design and the development and is based on conventional methods of analysis and procedural design concepts. The analysis module is for the analysis of various components of the suspension bridge like cables, suspender, stiffening girder, tower and anchorage. Dead load, live load, seismic load, wind load, vehicle impact load, effect of temperature variation and longitudinal forces are considered in the analysis. The design module deals with the design of various components mentioned above.

* Assistant Professor, Ilahia College of Engineering & Technology (ICET), Mulavoor P.O., Muvattupuzha , Kerala.

INTRODUCTION

The introduction of computer and software in civil engineering industry has greatly reduced the complexities of different aspects in the analysis and design of projects, as well as reducing the amount of time necessary to complete the designs. Concurrently, this leads to greater savings in costs. More complex projects that were almost impossible to work out several years ago are now easily solved with the use of computers. But most of the standard structural analysis programs appear as *black boxes* to their users with input going in at one end and solution magically appears at the other end. This study is mainly concerned with the structural theory and design procedures behind the structural programs and also the different steps involved in the development of a computer program for the analysis and design of structures.

OBJECTIVES

The main objectives of the study are:

- To review and report the literature available in analysis of suspension bridges.
- To develop software for analyse and design the elements of suspension bridge, using Microsoft VC^{++}.
- To employ a general finite element software for linear elastic analysis of suspension bridge and hence validating the results obtained from the computer code.

LITERATURE REVIEW

Suspension bridges are one of the most impressive types of bridge with their long main span and beauty. In suspension bridges, the deck is supported at relatively short intervals by vertical suspenders, which in turn are supported from main cables. The main cables are relatively flexible and thus take a profile shape that is a function of position and magnitude of loading. [1]

Components of Suspension Bridges

- Cables
- Suspenders
- Stiffening girders
- Supporting towers
- Anchorage

Economic Proportion

The minimum ratio of side span to main span is about ¼th for straight back stays and ½ for suspended side spans. Shorter ratios tend to make the stresses or sections in the back stays greater than the main cable.

The economic ratio of sag to main span of the cable between towers is about 1/9th, if the back stays are straight and about 1/8th if the side spans are suspended. For light highway and foot bridges, the sag ratio may be made as low as 1/10th to 1/12th.

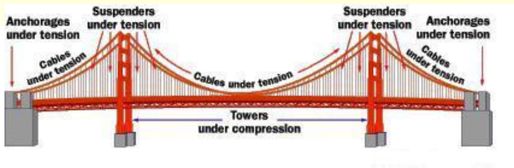
The economic depth of stiffening truss is about 1/40th of the span, although a shallower depth can be provided for aesthetical reasons. For Railroad Bridge, the truss depth should not be less than 1/45th of the span. For highway bridges, the depth may be made as low as 1/50th to 1/60th of the span. [1]

Assumptions

The theory developed for the analysis of suspension bridges with stiffening truss is based on five assumptions. [1]

- The cable is supposed perfectly flexible, freely assuming the form of the equilibrium polygon of the suspender forces.
- The truss is considered a beam, initially straight and horizontal, of constant moment of inertia and tied to the cable throughout its length.
- The dead load of truss and cable is assumed uniform per lineal unit, so that the initial curve of the cable is a parabola.
- The form and ordinates of the cable curve are assumed to remain unaltered upon application of loading.
- The dead load is carried wholly by the cable and causes no stress in the stiffening truss. The truss is stressed only by live load and by changes of temperature.

Structural Action



ANALYSIS OF COMPONENTS

Cable

Horizontal pull in the cable is calculated using the following relation. [1]

$$H_c = \frac{\frac{3}{f^2 l}\left[\int_0^l M' y dx + i\int_0^l M_1' y_1 dx_1\right]}{\frac{8}{5}(1+2ivr^2) + \frac{3l'}{E_c A}\frac{E}{f^2 l}(1+8n^2) + \frac{6}{f^2 l}\frac{El_2}{E_c A_1}\sec^3\alpha_1(1+8n_1^2)}$$

Stiffening Girder

With all three spans loaded, for any section in the main span,

$$\text{Total M} = \frac{1}{2}px(l-x)\left[I - \frac{8}{5N}(1+2ivr^3)\right] \text{[1]}$$

The maximum negative moment at any section of the main span is obtained by loading the length l - kl in that span and completely loading both side spans. Then,

$$\text{Min M} = -\frac{2}{5\text{N}}px(l-x)(D(k)+4ivr^3) \text{[1]}$$

where the function,

$$\text{D(k)} = (I-k)^2(2-k-4k^2+3k^3) \text{[1]}$$

The maximum positive moments are given by the relation,

$$\text{Min M} = \text{Total M - MinM} \quad \text{[1]}$$

Thus the maximum moment

$$\text{Max M} = -\frac{1}{2}px(l-x)\left[I - \frac{8}{5N}(I - \frac{1}{2}D(k)\right] \text{[1]}$$

With the three spans completely loaded, the shear at any section x in the main span will be

$$\text{Total V} = \frac{1}{2}p(l-2x)\left[I - \frac{8}{5N}(1+2ivr^3)\right] \text{[1]}$$

Loading the main span from the given section X to the end of the span, we obtain the maximum positive shears by

$$\text{Max V} = \frac{1}{2}pl\left(I - \frac{x}{l}\right)^2\left[I - \frac{8}{N}\left(\frac{I}{2} - \frac{x}{l}\right)G\left(\frac{x}{l}\right)\right] \text{[1]}$$

Where the func tion

$$G\left(\frac{x}{l}\right) = \frac{2}{5}\left(I - \frac{x}{l}\right)^3 - \left(I - \frac{x}{l}\right)^2 + \text{I} \text{[1]}$$

The maximum negative shears in main and side spans are given by the relations,

$$Max\ V = Total\ V - Min\ V \quad \text{[1]}$$

Tower

The loads acting on the tower are the vertical reaction (*V*) at the saddles, shear force from the stiffening girder and the balancing vertical forces due to seismic and longitudinal force.

The factored load for column is evaluated using

P_u = service load x partial load factor. [2]

The area of longitudinal reinforcement A_{sc} is calculated from the relation

$$P_u = 0.4 f_{ck} A_g + (0.67 f_y - 0.4 f_{ck}) A_{sc} \quad [2]$$

- Tie Diameter [2]

Tie diameter should be greater of the following

i. 6 mm
ii. n ¼th of the diameter of the largest diameter longitudinal bar

- Tie Spacing [2]

Tie spacing should be the least of the following.

i. Least lateral dimension of the tower
ii. 16 times diameter of least diameter longitudinal bar
iii. 300 mm

Anchorage

Following checks are done for anchorages.

- Check for sliding
- Check for tilting

Suspender

When the loads and the spacing of the suspenders is known, the load carried by each suspender can be found out. This load divided by the permissible stress of the suspender material gives the cross section of the suspender.

LOADING

Following loads are considered in analysis of various components.

- Dead load

- Live load [3]
- Seismic load [3]
- Impact load [3]
- Longitudinal forces [3]
- Temperature stresses [3]
- Wind load [4]

SOFTWARE GENERATION [5, 6]

Software for the analysis and design of suspension bridges was developed during the study. The following sections discuss the class diagrams and different components and capabilities of the software.

Class Diagrams

Cable
- sideSpan
+ mainSpan
- cArea
- dTension
- lTension
+ tTension
- totTension
- cSafeStress
+ cDeadLoad
+ cLiveLoad
+ I
+ alp
+ sagMain
+ n,
+ N
+ maxTension

- cAreaRequired

+inputCable
+ analyseCable
+ designCable
+outputCable

Anchorage

- aLength
- aBreadth
- aDepth
- aReaction
- aHeelPressure
- aToePressure
- alp1
-allowableSoilPressure
- aAngleOfFriction

+inputAnchorage
+ analyseAnchorage
+ checkAnchorage
+outputAnchorage

Girder

- gLiveLoad
- gWindLoad
- gSafeStress
- gTopChordRequired
- gBottomChordRequired

- gSpacing
- momentTable[6][12]
- shearTable[6][19]
+ gDepth
+ gTopChordArea
+ gBottomChordArea

+inputGirder
+ analyseGirder
+ designGirder
+outputGirder

Suspender

- sSpacing
- sLoad
- sArea
- sSafeStress
- sAreaRequired

+inputSuspender
+ analyseSuspender
+ designSuspender
+outputSuspender

Tower

- tBreadth
- tHeight
- tTopWidth
- tBottomWidth
- tH1
- tH2
- tH
- th

+inputTower
+ analyseTower
+ designTower
+outputTower

Bridge

- Cable
- Girder
- Suspender
- Tower
- Anchorage

+ input
+ analyse
+ design
+ output

Main Module

There are two modules in the software. Each module can be invoked by using 'Bridge Two Hinged Side span free' or 'Bridge Two Hinged Side span Suspended' menu item on the menu bar of the main window. These modules have only one window. Screen shot of the main window is shown in Figure 1.

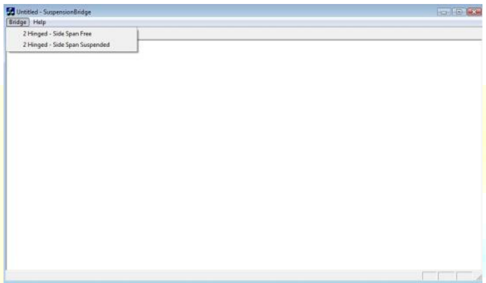


Figure 1. Main Window

Module for Bridge Analysis and Design (Type 2F)

This module can be invoked by using 'Bridge Two Hinged Side span free' menu item on the menu bar of the main window. This module has only one dialog box (window). The dialog contains a number of controls like text boxes, labels, lists, etc. Screen shot of the module is shown in figure 2.

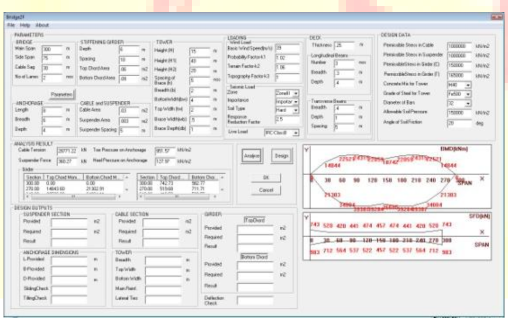


Figure 2. Module for Type 2F

Data to be input for analysis are:-

1.Details of Bridge: Main span, side span cable sag and number of lanes.

2. Cable and suspender cross sections.

3.Details of girder: area of top & bottom chord, depth & spacing.

4.Details of anchorage: Length, breadth and depth.

5.Details of tower: Height, Cross sectional details & bracing details.

6.Loading

Text boxes are provided to input the required values. To analyse the bridge, enter the data and press the Analyse button. The user will be prompted to enter the optimum values for side span and cable sag, when he input the main span. If any of the values are missing or not acceptable (like zero or negative value), the user will be prompted to correct such values.

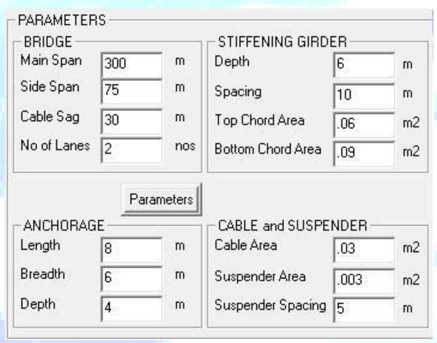


Figure 3. Input Data of Cable, Suspender Anchorage & Girder

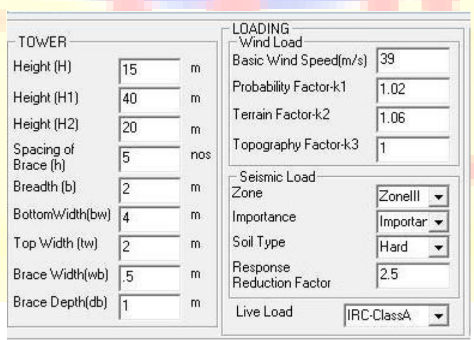


Figure 4. Input Data of Tower and Loading

Clicking the Analyse button will display the analysis result. The analysis result includes the tension in the cable, tension in each suspender, heel pressure and toe pressure acting on the anchorage, and the moment and shears force acting in top and bottom chord of the girder. The analysis result of girder is displayed for equal intervals of 0.1 times span.

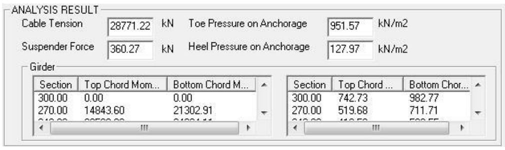


Figure 5. Analysis Results

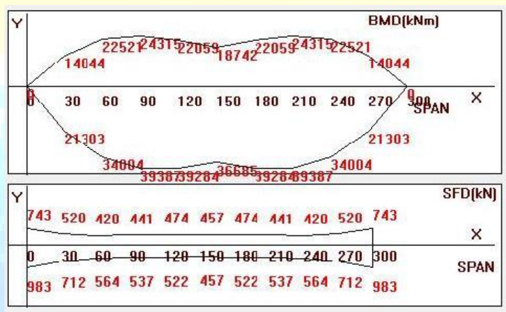


Figure 6 BMD & SFD of Girder

Design of Members

Once the analysis results are obtained, the design process can be started. Since most of the members are subjected to tension or compression, the design is an easy task. The following data are necessary for design.

a. Permissible stress in cable
b. Permissible stress in suspender
c. Permissible compressive stress in girder
d. Permissible tensile stress in girder [7]
e. Concrete mix for tower
f. Grade of Steel for tower
g. Diameter of bar
h. Allowable soil pressure
i. Angle of Soil friction

The screen shot of the module is shown in figure 7.

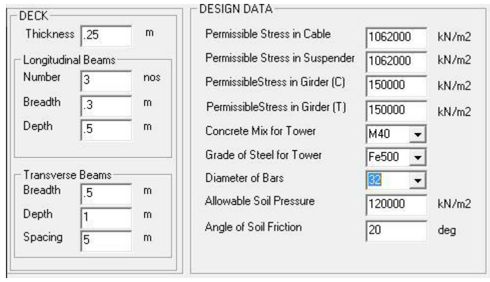


Figure 7. Design Data

When these data are input and the user clicks the Design button, the program will give the design output for each element, as shown in figure 8.

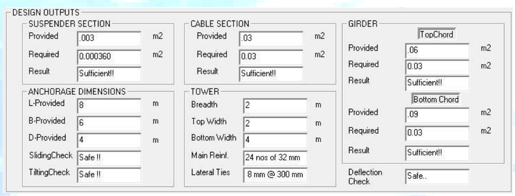


Figure 8. Design Output

The following results are obtained:

- Cable: cross sectional area required
- Suspender: cross sectional area required
- Girder: cross sectional area required for top and bottom chords
- Anchorage: stability against sliding and tilting.
- Tower: details of longitudinal and transverse reinforcement

Validation of Software with SAP

For validating the analysis results obtained from the software developed, the analysis of suspension bridge is carried out using SAP 2000. The input data required for the analysis of suspension bridge using SAP is listed below.

Overall Span	450 m
Main span	300m
Side span	75m
Minimum middle sag of the cable	10m
Spacing of suspender	5m
Width of deck	10m
Column height above deck	40m
Column height below deck	20m

Loading standards is IRC: 6 2000 loads and stresses

Two lanes of IRC Class A

Wind Loading

Wind forces are to be calculated as per clauses mentioned IS 875 Part III. Wind forces are considered acting perpendicular to the superstructure.

Seismic Loading

Seismic forces are calculated as per modified clause for the interim measures for seismic provisions (clause 222 of IRC: 6: 2000). Seismic forces are considered acting perpendicular to the superstructure.

Temperature Effect

The structure has to be checked for temperature effects as per clause 218.3 of IRC: 6-2000.

Materials used in construction

Concrete	Grade M 40
Steel	Grade Fe 500

High tensile steel: Class II, uncoated, low relaxation strands as per IS 14268 – 1995 and also confirming to Class 2 of IS 6006 – 1983, with a breaking stress of 1770 MPa.

Permissible Stresses

The permissible stresses in the various components of the suspension bridge are listed below

Reinforced Concrete

Direct compression	10 MPa
Flexural compression	13.33 MPa
Flexural tension	0.67 MPa

Reinforcing Steel

Direct compression 205 MPa

Tension in shear 200 MPa

Tension in flexure 240 MPa

Cable Suspenders and Girders

Direct tension in cable and suspenders 1062 MPa

Direct tension in girder 150 Mpa

Direct compression in girder 150 Mpa

Section from left end(m)	Moment (kNm)		Shear (kN)	
	Top	Bottom	Top	Bottom
0	0	0	705.85	933.45
30	13343.40	20025.76	489.04	685.29
60	21506.60	31623.31	395.67	538.93
90	23342.22	37220.71	419.23	523.06
120	21176.64	3692696	455.04	511.57
150	17805.95	34300.89	434.48	430.68
180	21176.64	3692696	455.04	511.57
210	23342.22	37220.71	419.23	523.06
240	21506.60	31623.31	395.67	538.93
270	13343.40	20025.76	489.04	685.29
300	0	0	705.85	933.45

Table 1. Output from SAP Analysis

Section from left end(m)	Moment (kNm)		Shear (kN)	
	Top	Bottom	Top	Bottom
0	0	0	742.95	982.58
30	14043.60	21302.91	520.26	712.35
60	22520.56	34003.56	419.66	564.33
90	24314.82	39387.78	441.31	537.24

120	22059.13	39284.23	473.86	551.93
150	18741.75	36685.45	457.35	456.23
180	22059.13	39284.23	473.86	551.93
210	24314.82	39387.78	441.31	537.24
240	22520.56	34003.56	419.66	564.33
270	14043.60	21302.91	520.26	712.35
300	0	0	742.95	982.58

Table 2. Output from Software

Comparison of Results

From the above values listed in the table it is observed that the approximate percentage variation in bending moments of top chord members of the girder from both methods of analysis is 4.3 %. There percentage increase in shear values obtained from the software analysis in comparison with SAP analysis is about 4.5 %. Similar trend is observed in case of bending moment and shear values in case of bottom chord members of the girder. The percentage increase in moment and shear value for the bottom chord members are 6.1 % and 5.2 % respectively. The software provides only the maximum tension in the cable and the percentage increase in axial pull when compared with SAP analysis is 3 %. The results from software when compared with finite element analysis is found to be satisfactory

REVIEW OF SOFTWARE

Advantages of Software

- It is user friendly, having a single window for each module, without the complexities and confusion of so many windows.
- It is extensible, as the software design is based on object oriented concept. Any enhancements or additions can be incorporated at a later stage, without any difficulty.

Limitations of Software

- It is not provided with an option for graphical input
- The module for analysis and design of bridge deck is not included

Proposed Enhancements

- Include a graphical input module
- Include a module for the design of bridge deck
- Include modules for the design of connections

CONCLUSIONS

The structural analysis of suspension bridge posses many difficulties because of the complex interaction between various structural components. Various manual methods are available for the analysis of suspension bridge and are briefly explained in literature review of the paper. But the manual calculations are lengthy, cumbersome and time consuming. Various software packages like STAAD Pro, SAP 2000 are available for the analysis.

For the preliminary analysis and design of suspension bridge, no exclusive softwares are available. Hence a strong need for generation of a custom made user friendly software for the analysis of suspension bridge is felt and it had been realized in the present study.

The following conclusions are made from the present studies

i. Custom made software is developed in Visual C^{++} for analysis and design of suspension bridges.

ii. User friendly methodology is adopted for interface design. All data are entered in a single form and the result of analysis is displayed in the same.

iii. The design module of the suspension bridge is integrated with the analysis which makes the understanding and use of software easier. The components designed here include cable, suspender, girder, anchorage and tower.

iv. The results obtained from the software were comparative with the finite element analysis results of SAP, the percentage variation being less.

v. The software is advantageous because it is exclusive and more adopted to the relevant codes.

SCOPE FOR FUTURE WORK

The scope of the present work is limited only to two hinged suspension bridge with side span free and suspended cases. This can be extended to continuous and semi-continuous bridges. The effort can be made to integrate a graphical input module to the software. The software being an extensible one can be used to incorporate modules for the design of bridge deck and connections. Further research and study is needed for the non linear analysis of the suspension bridge.

REFERENCES

[1] Steinman D.B., *"A Practical Treatise on Suspension Bridges"*, John Weiley & Sons Inc., New York

[2] IS: 456-2000 Indian standard. *Plain and reinforced concrete – Code of Practice* Bureau of Indian standard, New Delhi.

[3] IRC 6: 2000, *Standard Specifications and Code of Practice for Road Bridges*, Design Criteria for prestressed concrete Road Bridges (Post Tensioned Concrete), Third Revision, The Indian Road Congress, New Delhi, 2000

[4] IS: 875 (Part III)-1987, *Indian Standard Code of Practice for Design Loads (Other than earthquake) for Building and Structures*, Bureau of Indian Standards, New Delhi.

[5] Ivor Horton, *"Beginning Visual C++ 6"*, Wrox Press Ltd., Birmingham, UK.

[6] David J. Kruglinski, *"Programming Microsoft Visual C++",* Microsoft Press, U.S.A.

[7] IS: 800-2007 Indian standard. *General Construction in Steel – Code of Practice* Bureau of Indian standard, New Delhi.