COMPUTER MODELLING OF SUSPENSION BRIDGES FOR LIGHT VEHICULAR TRAFFIC

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ABSTRACT

Suspension bridges that can allow light vehicular traffic can be much more beneficial than pedestrian suspension bridges, since those will allow more economic benefits by facilitating the transport of goods. However such bridges are still not available in Sri Lanka. Therefore, it is useful to develop suspension bridges for light vehicular traffic that could be constructed with locally available expertise in modular fashion. In this study, the loads appropriate for such bridges are presented. The techniques for accurate computer modelling to determine the effects of various loading conditions are developed. Case studies were carried out for 42m and 60m span bridges to illustrate the design method.

INTRODUCTION

Sri Lanka is a country with many rivers. In many locations, the rivers are wide and carries large quantities of water during monsoon season. In order to link villages separated by these rivers, large bridges are built only at selected locations. In many other locations, suspension bridges built for pedestrians have become the preferred solution, due to cost considerations. However, such bridges cannot bring sufficient economic benefit to the rural communities since the crops and other items produced cannot be transported. In this respect, it is advantageous to have single lane suspension bridges that could allow light vehicles such as hand tractors with trailers, three wheelers, cars and vans. In this paper, the design methods for suspension bridges of 40 m to 60 m range is presented. In order to determine the design forces, computer modelling is used. The selection of the appropriate computer model and the determination of the cable stiffness for the computer modelling are also presented.

OBJECTIVES

The main objectives of the research study presented are the following:

1. To illustrate the need to develop suspension bridges that can allow a single lane of traffic.
2. Determination of suitable cable and deck arrangements for the suspension bridges that would allow a single lane of light traffic.
3. Selection of an appropriate computer model that could be used for the analysis.
4. Determination of the response of the suspension bridges when subjected to various probable loads.

METHODOLOGY

The following methodology was used to achieve the above objectives:

1. The spans required at a number of bridge sites were evaluated using the available data.

2. In order to allow light vehicular traffic, the deformations of the deck should be controlled to an appropriate level. The structural arrangement that would allow this type of desirable behaviour was developed.

3. The use of computer modelling of suspension bridges can give a more realistic idea about the actual behaviour of the structure. The design parameters are selected for the suspension cable and the stiffening girder. The loads appropriate for the light vehicular traffic are also selected. The special requirements for the computer model are also discussed.

4. A computer model selected was analysed for different loading conditions to determine the critical forces on cables, hangers and the members of the stiffening girders. The use of these to determine the member sizes are briefly discussed.

THE DETAILS OF THE PEDESTRIAN SUSPENSION BRIDGES

The details of the suspension bridges already constructed in various parts of Sri Lanka are evaluated to determine the spans that are likely to occur at various sites. These details are given in Table 1. These bridges indicate that the spans could be in the range of 60m to 80m. They are generally constructed across wide rivers or those with widely fluctuating water levels which makes it difficult to construct the substructure within the river.

Table 1 : The details of the suspension bridges already constructed

Location	Length of Main Span (m)
1) Bridge at Hallolluwa over Mahaweli Ganga	73
2) Bridge at Lewella over Mahaweli Ganga	73
3) Bridge at Botanical Garden, Peradeniya over Mahaweli Ganga	80
4) Bridge over Victoria Reservoir at Digana over Kumbukkan Oya	65
5) Bridge over Gin Ganga on Neluwa- Batuwangala road (Galle District)	63
6) Bridge over Gin Ganga on Neluwa- Thawalama road at Mawanana (Galle District)	63

THE STRUCTURAL ARRANGEMENT AND THE LOADS

Unlike in pedestrian suspension bridges, controlling of deformations in case of a vehicular bridge is a very important task. In this case, considering the ease of construction, a stiffening girder could be constructed in modular fashion. Each module of the stiffening girder is suspended from the hangers at 3.0m intervals connected to the main cables on either side. This will facilitate the erection of the stiffening girder from either end of the bridge incrementally. Each module consists of a 3.0m x 3.0m x 1.0m high steel box as shown in the figure below. The local effects of loads on the module can be determined with a simple 3D computer model for a space truss or a space frame.

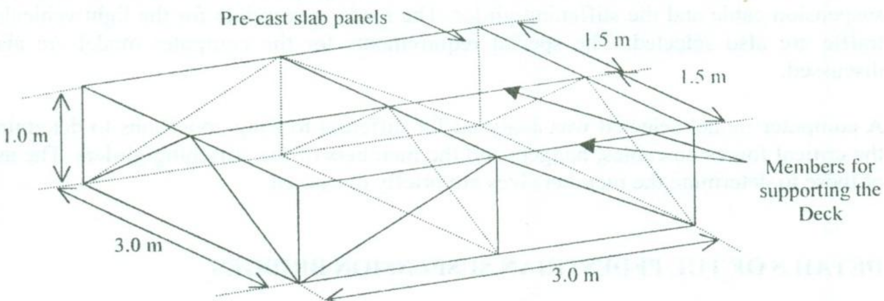
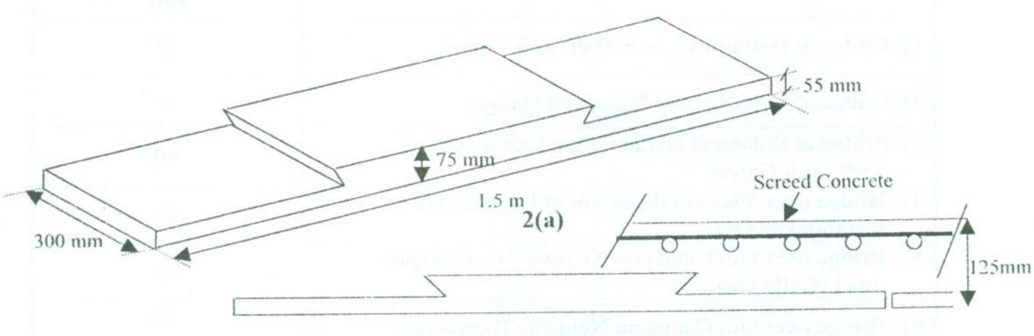


Figure – 1 : The structural arrangement selected for the stiffening girder

The deck could consist of pre-cast reinforced concrete slab panels laid side by side and later 75mm thick screed concrete could be laid over that to get the composite action of the deck. Figure 2(a) shows the details of the pre-cast slab which can be handled manually. Although, the width of each module is 3.0m, only a width of 2.5m will be reserved for the vehicles by using a hand rail. This will allow a space of 0.25m for any lateral movement of the cable due to loads.



2(b)

Figure 2: (a) The pre-cast Panel. (b) The arrangement of the slab panels with in--situ cast screed.

The Loads on the Bridge

Since there can be pedestrian traffic also in addition to the vehicular traffic, the bridge has to be designed for the live loads recommended for the pedestrian bridges. Since this bridge has an effective width of 2.5m, design live load is 5.0 kN/m^2 as specified in BS 5400: Part 2, using the reduction allowed for the spans larger than 30m.. If a light vehicle has a length of 5m, the corresponding pedestrian load is 5.0 x 2.5 x 5.0 = 62.5 kN. Thus, vehicles up to a weight of 6.4 tonnes can cross the bridge one after the other without exceeding the design live load. If an allowance of 25% is allocated (Appendix A of BS 5400: Part 2: 1978) for impact and vibrations caused by the vehicles, it would be safe to suggest that vehicles up to 5 tonnes could cross the bridge safely one after the other with close spacing. This would be quite sufficient for three wheelers, hand tractors, cars and vans. The laden weight of a van would be about 3.0 tonnes.

However, in practice, there is a possibility for an isolated vehicle, which is heavier than 5 tonnes to cross the bridge even if precautions are taken to prevent such vehicles entering the bridge. Therefore, the bridge can be designed for an isolated vehicle of weight 10 tonnes located at 1/8, 1/4, 3/8 and 1/2 span points as well. The effect of such a vehicle on the stiffening girder modules of length 3.0m also could be investigated to determine the local effect of a heavier vehicle. Therefore, the live loads on the bridge can be identified as given in Table 2.

Load Case	Description
Case 1	The live load corresponding to pedestrian traffic (5kN/m^2), which acts throughout the length of the bridge.
Case 2	The live load corresponding to pedestrian traffic acting on one half of the bridge.
Case 3	The live load corresponding to pedestrian traffic acting on ¼ of the bridge.
Case 4	The live load corresponding to pedestrian traffic acting within ¼ to ¾ of the span.
Case 5	The live load of 10 tonne crossing the bridge with the wheels located 4.0 m apart.
Case 6	The slabs supporting the carriageway will be designed for a wheel load of 3 tonne. This is calculated for the 10 tonne vehicle on the assumption that the 60% of the load will be taken by the rear axle which has two wheels.

Table 2: The details of the load cases

THE METHOD OF ANALYSIS

The first proper theory of suspension bridges is called the Rankine Theory. It is based on the two assumptions (Pugsley, 1968);

1. Under the total dead loading on the bridge the cable is parabolic and the stiffening girder is unstressed.

2. Any live loading applied to the girder is distributed so that the cable has to carry a uniformly distributed loading across its whole span.

Another theory developed for the analysis of suspension bridges is the "Elastic Theory". This represents an advance on Rankine theory where the cable forces are not considered as uniformly distributed. In this, reasonably accurate assessment is made for forces in hangers by using energy theorems (Pugsley, 1968).

For the present work, it was decided to use computer modeling since it could indicate the effects of loading clearly for different load cases for both suspension cable and the stiffening girder.

Computer Model Used

The model used for the computer analysis of the structure is given in Figure 3. In the case of a suspension bridge, the main cables run over a pulley which is fixed on top of the tower. The main cable is free to move over the pulley. This situation has to be accurately modelled in the the computer analysis. Another condition that needs accurate representation in the computer model is the fact that there can be a certain sag in the cable. If the cable is modelled as a member between two points, the program assumes it to be straight.

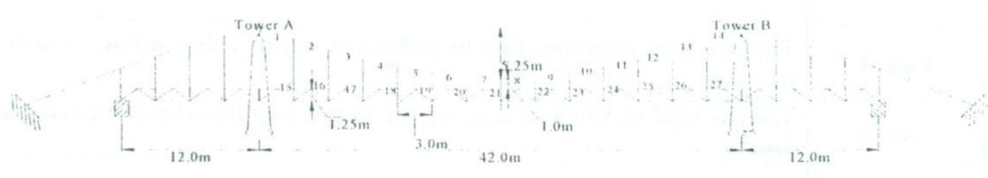


Figure 3: The model of the structure used for the computer analysis

The bridge is modelled on both Microfeap (P1) and Super Stress Version 4.3 computer programs. Super stress offers additional facilities like members which carry tension only; thus if there is any upward movement of the stiffening girder, the effects of such movements also can be accurately modelled. In most instances both programs gave the same answer.

50 mm diameter galvanized wire ropes of breaking strength 180 kg/mm^2 were used for the main cables. All the members of the stiffning girder consist of angle irons, tee sections and channel sections which can be handled manually.

Modelling of the pulley

If a pin directly supported on the tower is used for the model, it would not accurately model any movement in the cable. This could introduce some errors to the cable forces. This can be overcome by using the special arrangement shown in Figure 4.

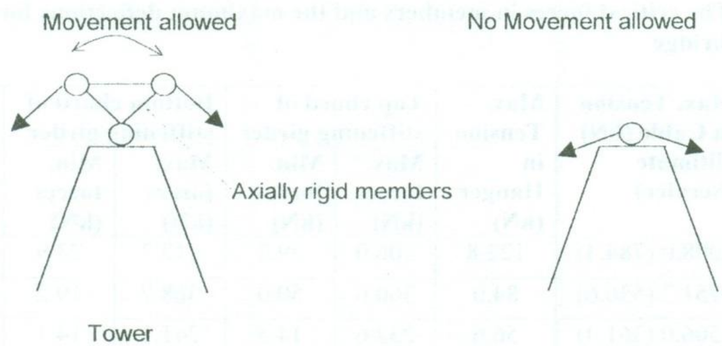


Figure 4: (a) The cable arrangement used over the tower to allow movement. (b) The use of a pin will not allow movement

The Stiffness of the Cable

In the case of a suspension bridge, the main cable has a parabolic shape and hence it gives certain amount of sag. This sag reduces the stiffness of the cable. It is shown by Tamhankar (1976) that for calculation purposes, an equivalent modulus (E_i) should be used in order to incorporate the sag. The value of E_i is given by:

$$E_i = \frac{E_c}{1 + \frac{(\gamma L)^2 . E_c}{12\sigma^3}}$$

where E_i - Equivalent Modulus
E_c - Elastic Modulus of the cable material
L - Projected plan length of the cable
γ - Specific weight of the cable
σ - Stress in the cable

In this case a value of 190 kN/mm^2 was used for the equivalent modulus of the main cable whereas its material has an elastic modulus of 200 kN/mm^2.

RESULTS AND ANALYSIS

The results of the analysis are presented in tabular form in Tables 3 and 4 for 42m and 60m spans respectively. The tabulated forces are for the Dead and Live Loads together. The forces in web members are not represented since those are found to be relatively small.

Table - 3: The critical forces in members and the maximum deflections for the 42m bridge

Load Case	Max. Tension in Cable (kN) Ultimate (Service)	Max. Tension in Hanger (kN)	Top chord of stiffening girder		Bottom chord of stiffening girder		Max. deflection in the stiffening girder (mm)
			Max. forces (kN)	Min. forces (kN)	Max. forces (kN)	Min. forces (kN)	
Case 1	1098.0 (784.3)	122.8	206.0	39.2	212.2	23.9	65.4
Case 2	751.2 (536.6)	84.0	360.6	50.0	368.7	19.2	66.6
Case 3	506.0 (361.4)	56.6	232.6	14.5	241.1	14.1	37.3
Case 4	582.0 (415.7)	99.8	256.4	37.7	266.8	3.4	64.6
Case 5	339.8 (242.7)	58.3	153.3	12.4	168.8	4.7	36.1
Case 6	-	-	0	0	18.9	10.3	-

Table - 4: The critical forces in members and the maximum deflections for the 60m bridge

Load Case	Max. Tension in Cable (kN) Ultimate (Service)	Max. Tension in Hanger (kN)	Top chord of stiffening girder		Bottom chord of stiffening girder		Max. deflection in the stiffening girder (mm)
			Max. forces (kN)	Min. forces (kN)	Max. forces (kN)	Min. forces (kN)	
Case 1	1450.0(1035.7)	88.5	280.2	18.2	285.0	9.1	108.6
Case 2	916.5 (654.6)	56.0	498.0	38.7	506.7	7.8	114.3
Case 3	661.5 (472.5)	40.4	346.6	11.0	355.7	28.8	67.5
Case 4	993.7(709.8)	60.7	345.4	35.7	353.1	22.4	96.9
Case 5	637.4(455.3)	38.9	159.0	7.9	171.4	3.0	54.1
Case 6	-	-	0	0	18.9	10.3	-

It can be seen from all these loading cases that the maximum cable forces occur when the whole span is loaded. The maximum hanger and stiffening girder forces occur when the main span is fully loaded and halfway loaded respectively.

It should also be noted that the forces obtained for the global analysis should be coupled with the forces obtained due to any local effects as well. Based on the results, it can be suggested that the use of 3 Nos. 50 mm diameter cables on one side would be sufficient to carry the maximum load on the structure in case of 42m main span and 6 Nos. 50mm diameter cables for the 60m main span. The factor of safety used for the selection of cables is 5.0. This was applied for the service loads obtained for the cable.

TOWER DESIGN

The towers of modern suspension bridges are broadly of three types.

(i) Stiff towers (either concrete or steel) fixed at their bases that support the main cables through a carriage that is free to slide or roll horizontally on the tower top, so that the tower itself offers a resistance to the vertical and horizontal components of the cable pulls.

(ii) Towers that are hinged at their bases so that they are free to rock in the plane of the main cables, which are securely attached to the tower tops.

(iii) Towers that are fixed at their bases and have the main cables secured to the tower tops.

All three types of towers are usually called upon to support not only the main cables at the tops but also the stiffening girder at a lower level. In this study tower type (i) was used and the main cable runs over a pulley which is fixed at the top of the tower. It consists of two tapered concrete columns, which have wider bases below the stiffening girder level and are connected by a strut at the top of the tower.

The tapered column is designed as a vertical cantilever and the bottom wider base below the stiffening girder will give a lateral and a torsional support.

ANCHOR BLOCK DESIGN

In case of a suspension bridge, the anchor block will be a costly item as it mainly depends on the ground conditions. If sound rock is available at a shallow depth the anchoring could be directly done to the rock or the anchor block could be well doweled into the rock in order to resist the sliding force. In situations where sound rock or any hard strata is not available anchor block will be a massive structure causing more construction cost. Hence, in such situations it is proposed to construct a cellular type gravity structure which can be filled with rubble in order to increase the dead weight in resisting the sliding forces as shown in Figure 5.

A tentative cost estimate for a suspension bridge of 40 m main span was prepared and it was found that cost estimate for the entire construction would be 19 Million Rupees.

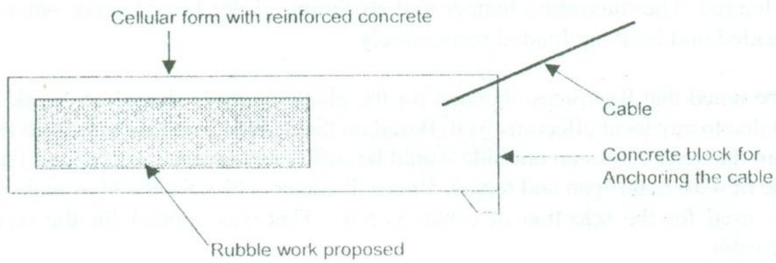


Figure 5: The proposed arrangement for the anchor block

CONCLUSIONS

This paper presents a structural arrangement that can be adopted for suspension bridges designed to carry light vehicular traffic. It is shown that the arrangement selected allows the construction of the bridge from both ends of the bridge in modular fashion. This is of particular importance since the bridge could be constructed by using the locally available expertise and resources. A suitable computer modelling technique is also presented which allows the design engineer to consider the effect of a number of load cases. The basis for the load cases was highlighted. In future, when pedestrian suspension bridges are planned, it would be possible to consider the alternative suggested for the light vehicular traffic. If the extra cost could be justified based on the potential benefits, it would be possible to adopt these bridges.

ACKNOWLEDGEMENTS

The assistance provided by the Road Development Authority and the Department of Civil Engineering in Moratuwa University is acknowledged.

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