The International Journal of Engineering and Science (IJES)
|| Volume || 10 || Issue || 3 || Series I || Pages || PP 15-33 || 2021 ||
ISSN (e): 2319-1813 ISSN (p): 20-24-1805

Comparative Design of a Balanced Cantilever Bridge In Java And Eurocode

Umeonyiagu I.E. [1], Onwuka F.E.[2], Ogbonna N.P[3].

1. *Department of Civil Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria.*
2. *Department of Civil Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria.*
3. *Federal polytechnic Nekede Owerri, Nigeria.*

---***ABSTRACT***---

This research analyzed, designed and detailed balanced cantilever bridges to Euro codes using manual and computer methods. The design was done considering only the superstructure which forms the dynamic element as a load carrying member. A Java based computer program to analyze, design and detail the balanced cantilever bridge was also written. The Java program focused on the design of prestressing cables for box-girder bridges using balanced cantilever method. The program made use of algorithms and visualization techniques. The segments of the bridge ranged from 15 to 48. The maximum number of cables was 819. Also the maximum number of strands was 9822. The maximum bending moment and shear force were 5790000kNm and 44362.5kN respectively. The manual design were done for 100m, 150m 200m 250m and 300m main spans. These results were then compared to the results gotten from the Java computer program. It could be seen that the results of both analyses and designs obtained using manual procedures and computer program were approximately the same. Furthermore, the percentage difference results showed very little or no differences between the various results obtain from both manual and computer program analyses. The results showed that the developed computer program had been validated with Eurocodes BS EN 1992-1-1 and EN 1992-2 and can serve as a reliable and handy tool for the analyses and design of balanced cantilever bridges. Eurocodes BS EN 1992-1-1 and EN 1992-2 can be applied easily by using this Java program to design cables based on factors of safety, serviceability, economy and elegance. The Java program also contributes to the performance in terms of suitability and reliability. It also gives quick and accurate analyses and design of balanced cantilever bridges.

Keywords: *Comparative Design of a Balanced Cantilever Bridge in Java and Eurocode*

Date of Submission: 11-03-2021 Date of Acceptance: 26-03-2021

I. INTRODUCTION

According to Prayful and Hanumant (2015), a bridge can be defined as structure providing passage over an obstacle without closing the way beneath. The passage may be used to construct a road, a railway, pedestrians, a canal or a pipeline. The obstacle to be crossed may be a river, a road, railway or a valley. Bridge design and construction is one of the most challenging issues for a structural engineer. Considerations must be made with respect to structural systems, construction materials, foundation types, or execution processes that are based on structural performance, construction and maintenance costs, local conditions, and aesthetics. A bridge consists of the superstructure, the substructure, and the foundation. The superstructure may be constructed from plate, box, or truss girders that act alone or are supported by arches, portal frames, stay cables, or suspension cables.

The substructure includes the abutments, the piers, and any pylons or towers. The materials used for construction of super-structure and substructures may be stone, timber, steel, and reinforced or prestressed concrete. Structural engineers are the main actors in the design of bridges (Vayas and Iliopoulos, 2014). Concrete slab and girder bridges are the most common bridge types. Slab and girder bridges can be

easily constructed and are used when the economical span limit of solid slab bridges are exceeded. For simply supported spans, this limit is generally found to be nearly 10 meters and for continuous or balanced cantilever type structures, this limit is 20 to 25meters (Shreddha, 2016). Tee beam deck slab bridges are the principal type among the cast-in-place concrete bridges, and consists of main girders, cross girders which impart lateral rigidity to the deck slab and deck slab which runs between T-beams continuously (Manohar and Chandra, 2018). Balanced cantilever bridges are adopted for comparatively longer spans where simply supported, continuous or rigid frame type superstructures are found unsuitable. Simply supported decks of any type having spans more than 20m to 25m require comparatively greater depths and therefore, become uneconomical (Shraddha, 2016).

Following a decision by the European Commission to develop harmonized technical specifications in the field of construction, and after an effort of almost 40 years, the Eurocodes were prepared to be used as design codes in replacement of national standards. By the correct use of the Eurocodes and all underlying standards, it is demonstrated that construction works including bridges are sufficiently safe (Vayas and Iliopoulos, 2014). Okonkwo, et al., (2019) presented three models of slab on beam bridge with varying number of girders and varying span lengths which were loaded with Load Model 1 (LM1) according to Euro code 1 Part 2 (EN 1991-2:2003) and analyzed using Finite Element Analysis, Grillage Analogy, and Courbon's method. They proposed a calibration factor for the results from Courbon's method as a function of the bridge span length, which will enable Courbon's method to be used as a quick check for verification of results from computer methods.

Davidson (2014), studied the design choices and their influence on the shear force design of reinforced concrete bridge decks. He investigated how different shear force design choices influence the final design of reinforced concrete bridge decks in terms of shear reinforcement. The results showed that there was not much difference between the various methods as regards to the shear force and the distribution widths for peak shear forces obtained in a linear analysis. Kesarwani, et al., (2018), analyzed T-beam bridges and obtained the value of bending moments, shear forces and deflection for different span ranges which were compared with the software, STAAD Pro V8i results. Al-Saraf, et al., (2005), performed the analysis of composite bridge superstructures using Modified Grillage method. From their analysis, it was found that the modified Grillage method gives a simpler method and gave adequate results when compared with the finite element method or orthotropic plate theory solved using finite difference method.

Mahadevan (2005) developed a computer code for building skew bridges. As a precursor to his program, he calculated the moments and the shear forces in a right bridge and simplified the working of a semi-continuum method. Prayful and Hanumant (2015), carried out a comparative study on the behavior of simply supported reinforced concrete T-beam bridge with respect to span moments under standard Indian road congress loading. Their study was based on the analytical modeling of reinforced concrete T-beam bridges by rational method and finite element method for different spans. Ajay, et al., (2017) worked on the economical depth of a longitudinal girder for different span. He developed monogram's which can be used as a handy tool in the design of T- beam bridge. Manohar, et al., (2108) studied the analysis of a single span two lane T-beam bridge by varying spans of the bridges, deck slab depth using software SAP 2000. Arimanwa, et al., (2019) worked on computer based demonstrations of structural analysis for engineering students. He developed over a hundred instructional program used in teaching and simulating structural behaviors. Onyenuga (2011) demonstrated in his book how to design reinforced concrete structures using both manual approach and computer based approach (using Fortran programming Language).

German engineers first used cast-in-place cantilevering in 1950 for a 62-m long span, as Fletcher (1984) reports. However, the cantilevering method is much older and had already been used in Asia for wooden structures of the earliest times, according to Podolny and Muller (1982). Shraddha (2016), performed manual analysis and design of balanced cantilever bridges under IRC loading. Jitha and Rajamallu (2016), worked on girder design of a balanced cantilever bridge with analysis using Midas civil software program. From their results, it was observed that less concrete, steel and formwork are required for cantilever designs, the reactions at the piers are vertical and central permitting slender piers, the cantilever design required only one bearing at every pier but simply supported design need two bearings. Hence, the width of the pier can be smaller. Fewer expansion bearings are needed for the full structure, resulting in lower first cost and maintenances.

A comprehensive study about design of box-girder bridge using balance cantilever method was presented by Benjamin (2015). His thesis discussed the methodology used to design balanced cantilever bridge and touched on the type of box-girder used for bridge and construction method used for constructing bridge using balance cantilever method. Method of construction is main concern in designing balance cantilever bridge where load apply during construction to the structure need to be determine before designing the bridge. Other study about conceptual design of long-span cantilever constructed concrete bridges was performed by Honorio (2007).

SAP2000 was used to carry out the linear analyses of these box girders. In order to analyze the complex behavior of the different box girders, they employed three dimensional 4-noded shell elements for discretization of domain. Saxena and Maru (2013) carried out a comparative study of T-beam girder and Box girder superstructures. The goal of the study was to determine comparative results obtained from manual and the computer methods (Java program and commercial finite element program like STAAD-PRO). Misal (2014) carried out a study on design and cost analyses of pre-stressed concrete girder. In this paper balanced cantilever bridge were analyzed manually and secondly with a Java program. These results are then compared with the results obtained for the same by using the STAAD PRO software. The quantities of concrete and steel required for both girder are analyzed. Bhivgade (2014) carried out a study on the analyses and design of pre-stressed concrete box girder. She checked at various span/depth ratios, the deflections and stress criteria. Garg and

Kumar (2014) analyzed the several positions in a box girder where the pre-stressed tendons can be added. By keeping constant the loading and varying the positions of tendons, a comparative study was done so as to understand the most effective positions of pre-stressed tendons.

The authors (Garg and Kumar, 2014) reviewed several researches on box girder over the years like the development of curved beam theory by Saint Venant (1843) and thin walled beam theory by Vlasov (1965). They did a complete analysis of a bridge section with the addition of pre-stressed tendons and the loading was done on SAP2000 software. The stress tendons were added to bridge sections at various positions in different combinations. Various combinations of these positions were analyzed so as to find the most effective combination. In the research tendons were added in two parts each over the complete span of the deck section. A combination of three moving vehicle loads i.e. H 20-44 Truck load, HS 220-44 Truck load, H 20-44 Lane load in two lanes of bridge deck was considered. The conclusion of entire analyses was obtained by comparing the stress contours of the different case. In the 1st case when tendons were added over the entire top span and the over-hanging part of the box girder, the displacement reduced considerably. In the 2nd case when the tendons were added at the bottom of the structure in addition to the top span the bridge becomes more stable compared to previous case. In the 3rd case, when tendons were added to the slant edges there was no considerable change in the stability of the bridge.

Khalil (2015) investigated the behavior of the box beam girder under pure torsion. He described various methods for torsional strengthening of concrete box beams. In their search, the box beam was strengthened experimentally with external pre-stressing technique using two different directions horizontally and vertically. Also a computing procedure was developed to predict torsional capacities of the box beams under torsion and the results were compared with the experimental one. In the study, ten strengthened box beams using external pre-stressing technique with and without web opening were tested. The study emphasizes pre-stressing direction and transverse opening dimensions. The torsional capacities, failure modes, stress in external tendon and strain in internal reinforcement were studied in detail. The experimental results indicated that the contribution of external pre-stressing technique for horizontal and vertical direction to torsional capacity of box beam with and without opening was significant, with ratios ranging from 31% to 58% respectively. It was found that the presence of transverse opening decreases the torsional capacity compared to beam without opening, the result proposed and modified equation of Egyptian code and of box beam (Khalil, 2015).

Sasidharan (2015) presented a parametric study of curved box girders by varying spans and radii of curvature and by keeping the span to depth ratio constant. The cross section adopted for the model was a single-cell rectangular type box-girder having 7.5m width, 2-Lanes carriageway with overall deck width of 8.5m. The thickness of the top deck slab was 240mm at the middle, 300mm at the web and 200mm at ends. The thickness of both soffit slab and webs were 240mm. The overall Span lengths considered were 20m, 30m and 40m. Seven different radii of curvature such as 75m, 90m, 100m, 150m, 200m, 250m and 300m were considered. A span-to-depth ratio of 16 was adopted.

II. LITERATURE REVIEW

2.1 Construction of Segmental Bridges

Concrete segmental bridges were built as early as 1925 (Plougastel Bridge) by French engineer Freyssinet (1879-1962), who was among the first to implement prestressed concrete in bridge construction. Since then, prestressed concrete bridges, both as pre-tensioned and post-tensioned had seen a rapid development. In most cases, post-tensioning was employed, i.e. the prestressing tendons were stressed with hydraulic jacks after the concrete has been placed and gained a minimum strength (Menn, 1990). Usually, the post-tensioning tendons are located in steel ducts within the concrete segment and were terminated in special anchorages (Lucko and Garko, 2015).

Concrete segmental bridges utilized box girder superstructures, which according to Troitsky (1994) have been used in the U.S. since 1973. These superstructures consist of bottom slabs, webs (that can be inclined), and a cantilevering top slab to provide maximum deck width. Concrete box girders have multiple advantages, for example their versatility in alignment, width, and depth, high torsional and bending stiffness of the closed cross-section, and an aesthetically pleasing geometric appearance. Segmental construction is a method of construction in which primary load-carrying members are composed of individual members called segments are post-tensioned together (Podolny and Muller, 1982).

Segmental construction limitations logically follow from the technical limitations of erection methods and the construction equipment. Cranes, concrete pumps, form travelers, and other pieces of equipment have certain physical limitations as to the volume and weight of material that can be erected at one time. Subdivision of the superstructure into segments can be made both in the transverse and the longitudinal direction. Separation of segments in the vertical axis is found less frequently (Podolny and Muller, 1982).

Vertical segmentation is used for example in composite bridge superstructures that consist of steel beams, trusses, or steel box girders with a concrete deck slab. Longitudinally divided segments are load carrying members that span the complete length of one bridge span, e.g. the use of multiple prestressed concrete (American Association of State Highway and Transportation Officials) girders, which are laid parallel and then covered with a deck AASHTO 2000. The erection of segments divides the overall construction process into repetitive steps that facilitate a learning process and improving productivity in the subsequently erected spans (Fletcher 1984).Segmental construction thus leads to economic and rapid erection of the bridge superstructure. A major advantage of segmental construction also is the ease with which it can be adapted to the specific requirements of the project (example geometry, span lengths, etc.) and to the capacity of the equipment available to the contractor.

2.2 Cantilevering Method

Cantilevering is an erection method in which individual bridge segments (the primary load carrying members) are sequentially erected at the tip of the self-supporting superstructure. Post-tensioning with longitudinal prestressing tendons is employed to hold the segments in the cantilever arms (i.e. span halves) together and to provide the needed moment resistance to withstand dead loads and live loads. The cantilevering method can be applied to both precast and cast-in-place constructions. Particularly for cast-in-place construction, the influence of the early loading of newly cast segments as well as the different segment ages in the superstructure need to be considered in the structural analysis of the erection process (Lucko and Garko, 2015).

2.3 Computerized Design of Box-Girder Bridges using Balanced Cantilever Method

The balance cantilever method is a method of construction where the segment is needed to be constructed from pier. Balance cantilever method is suitable for long span bridge especially for crossing wideriver and minimizes construction site at ground level. Balanced cantilever bridge is so named due to its method of construction. It is one of the most efficient methods of building bridges without the need of false work. This method has great advantages over other forms of construction in urban areas where temporary shoring would disrupt traffic and services below, in deep gorges, and over waterways where false-work would not only be expensive but also a hazard (Bundiman and Yassin, 2015).

2.4 Concluding the Cantilevering Process

The cantilevering process will finally have reached its end when both girders meet at mid-span and need to be connected. Three different ways exist to achieve this connection in the structural system (Mathivat 1983). A hinged connection can be installed that allows horizontal movements in the superstructure. As Mathivat (1983) writes, this system is structurally relatively simple, yet the hinges are complicated details and the overall structural redundancy of the system is reduced. Podolny and Muller (1982), also mention the lower ultimate load-carrying capacity of the hinged system and the higher susceptibility to creep and relaxation phenomena. Furthermore, the two superstructure halves can have a slight angle between them as deflections occur, which is detrimental to "the appearance of the bridge and the user's comfort" (Podolny and Muller 1982, p36).

Secondly, part of the mid-span superstructure can be designed as a suspended span sitting on bearings between the cantilevers. In this configuration the deflection angle between the shorter cantilevers and the suspended span will be much smaller, and "differential settling of the supports" can better be accounted for (Podolny and Muller 1982, p38). Still, the connections require special details in the structural system.

2.5 Traffic composition

In EN-2-1991, (1991) four load models are considered for vertical loads and they are:

i. Load Model 1 (LM1): This generally reproduces traffic loads which are to be taken into account for global and local verifications. It is made up of concentrated loads and uniformly distributed load.
ii. Load Model 2 (LM2): This load model reproduces effects on short structural members. It is comprised of a single axle load on a specific rectangular tire contact areas.
iii. Load Model 3 (LM3): Special vehicles to be considered on request, in transient design situations. It represents abnormal vehicles not complying with national regulations on weight and dimensions of vehicles.
iv. Load Model 4(LM4): Crowd loading Load Model 1.

The Load Model 1 which represents the effects of normal traffic comprises of tandem axles (TS) superimposed over a uniformly distributed load (UDL) whose intensity remains constant with the loaded length. The model is very different from Type HA loading given in BD37 (1991). Type HA loading consists of a uniformly distributed load, the intensity of which varies with the loaded length, and a constant Knife Edge Load (KEL) of 120kN. There are also lane factors for different lengths which account for simultaneity of loading in adjacent lanes as a function of loaded length. Eurocode (EN 1991-2) (2003), load model also differs from BD37 in the way that the carriage way is divided into notional lanes (Atkins Highways and Transportation, 2004). In EN 1991-2, the notional lane width is constant at 3.0m except for a small range of carriageway width between 5.4m and 6.0m, when the lane width varies from 2.7m to 3.0m

2.6 Object-oriented Approach to Finite Element Programming

Computer programming packages are available for analysis of thermal effects on bridges. Most of the software like STAADPRO are sold as commercial packages and will require adequate training to use. Computer programs can also be written to validate the results of manual analyses and to reduce the time spent as well as the error made during manual calculations. Several object oriented programming languages have been developed in recent years. These include C++, C#, and Java. Java is one of the more popular object oriented programming languages because it has several unique features. During the last fifteen years, finite element development has gradually shifted from procedural approach (Fortran, C) towards an object-oriented approach. Mostly, object-oriented finite element algorithms have been implemented in C++ programming language. It was shown that an object-oriented approach with the C++ programming language could be used without sacrificing computational efficiency compared to Fortran (1993).

2.7 Java Programming Language

The Java language, introduced by Sun micro systems over two decades ago, possesses features that make it attractive for use in computational modeling. Java is a simple language (simpler than C++). It has a rich collection of libraries implementing various application program interface. Java makes it easy to create graphic user interface and to communicate with other computers over a network. With Java memory, leaks are prevented with built-in garbage collection mechanism. Another advantage of Java is its portability. Java virtual machines (JVM) are developed for all major computer systems. JVM is embedded in most popular Web browsers in form of applets. Applets can be downloaded through the internet and executed within a web browser. Useful for object-oriented design, Java features are packages for organizing classes and prohibition of class multiple inheritance. This allows cleaner object-oriented design in comparison to C++.

2.8 The deformation problem of balanced cantilever bridges

According to Takacs (2002), concrete cantilever bridges built with the balanced cantilever method have become very popular due to the many advantages offered by the construction method and the structural form. Nowadays segmental, cast-in-place concrete cantilever bridges are routinely built in the 200m to 300meter span range while the longest span of this type is 301 meter. Segmental cast concrete cantilever bridges often exhibit larger deflections than predicted in the design calculation. The excessive deflection can lead to the deterioration of the aesthetic of the bridge and may reach the level where serviceability and traffic safety are compromised. The many cases where long-term deflections significantly exceeded the expected deflections have made design engineers and researches aware of the deformation problem in this type of structure. Deflections of the superstructure are large due to the slender and long free concrete span and the fact that the permanent loads are only partially compensated by the prestressing. The deformations are increasing with time over the entire life span of the bridge, although in a decreasing rate (Takacs, 2002).

2.9 Applicability of Box Girder for Balanced Cantilever Bridge

According to Redkar and Salunke (2016), initially naturally available materials such as stone and timber were extensively used for construction of bridges. From such ancient techniques, man derived prototypes to form structurally strong and stable structures. The efficiency and sophistication of design and construction kept pace with advances in science, material and technology. The earliest construction of permanent bridges started around 4000B.C. Bridge construction received a spurt with the advent of reinforced and pre-stressed concrete. The development of pre-stressing system by Freyssinet (1928-1936) gave further practical application to the construction of bridges. The next generations of bridges were made of steel and were first used in the Eads bridge at St. Louis, Missouri (1874). The use of steel led to the development of cantilever bridges. The world's longest span cantilever bridge was built in 1917 at Quebec over St. Lawrence river with main span of 549m. India can boast of one such long bridge, the Howrah Bridge, over river Hooghly with main span of 457m which is fourth the largest of its kind. Concrete cantilever construction was first introduced in Europe in early 1950's and it has since been broadly used in design and construction of several bridges.

III. MATERIALS AND METHODS

3.1 Bridge Design Specification

The balanced cantilever bridge is expected to pass a river with a main span of 100m and two side spans of 60m. Using the balanced cantilever method with precast segments and travelling formwork, the bridge is to be connected with a bridge of a total length of 220m. The carriageway of the proposed bridge consists in each direction of two traffic lanes, a hard shoulder, and a hard strip and on both sides, parapets from Table 3.1 and also shown in figure 3.4.

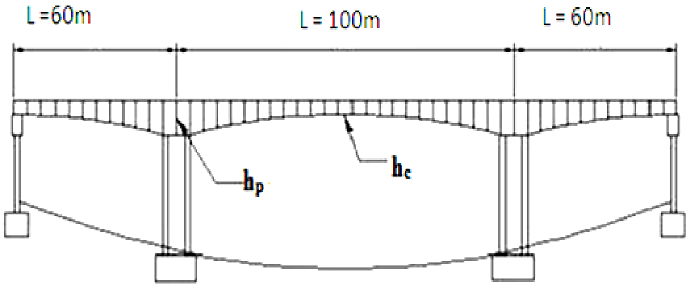


Figure 3.1 Bridge Specification

Table 3.1 Dimensions of the specific Elements of the carriageway

Element	Width (m)
Traffic Lane	3.50
Hard Shoulder	3.50
Hard Strip	1.50
Parapet	0.30

3.2 Load Model 1 (Section 4.3.2 of BS EN 1991-2:2003)

For the load-distribution, only LM1 has been taken into account. For this load case, we have to divide the bridge into notional lanes. Since the width of the bridge (12.6m) is bigger than 9m, the bridge deck contains 3 notional lanes and remaining area. The lanes have a width of 3m each, which means that the remaining area is 3.6m width. The loading configuration on the bridge is shown in Figure 3.2. The axle loads are as follows:

300 kN for lane 1,
200kN for lane 2
And 100 kN for lane 3

Each lane contains 2 axle loads, divided over 2 tires.
Each lane contains 2 axle loads, divided over 2 tires.

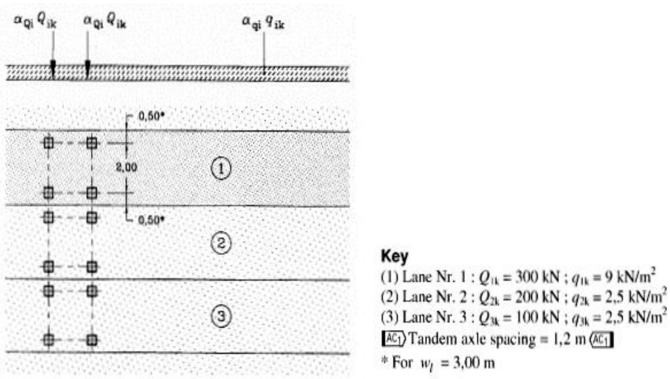


Figure 3.2 Application of load Model 1 (BS EN 1991-2:2003)

For the axle loads, it is assumed that the load is distributed in transverse direction under an angle of 45 degrees. So, travelling from both edges of the contact areas (400mm x 400mm) of the tires to the center of gravity of the beams with this angle, gives us the total effective width over which the load is spread.

Applying Load Model 1 of BS EN 1991-2:2003 and EN Consequence Class 3 the design calculations will be performed for the main span for other spans of 150, 200m, 250m and 300m using the thumb rule method to estimate the sizes of the cross section of the box girder.

Table 3.2 Load model 1: characteristic values [BS-EN 1991-2:2003, Table 4.2.

Location	**Tandem system TS**	**UDL system**
	Axel loads Q_k (KN)	**q_{ik} (or q_{rk}) (KN/m^2)**
Lane Number 1	300	9
Lane Number 2	200	2.5
Lane Number 3	100	2.5
Other lanes	0	2.5
Remaining area (q_{rk})	0	2.5

The effect of the axle loads are modeled by three different load cases according to BS-EN 1991-2:2003 from the table above:
$Case\ 1$: $2 \times 100kN\ on\ lane\ 1$; As regards to table 3.2
$Case\ 2$: $2 \times 100kN\ on\ lane\ 1\ and\ 2$;
$Case\ 3$: $2 \times 100kN\ on\ every\ lane$;
When these three load cases are summed up, the load case according for the axle loads is obtained again.

3.3 Design Calculations for the 100m main Span

It is assumed that two separate bridges will be constructed for the both directions. To estimate the height of the single cell box girder bridge, the following thumb rules will be adopted according to Sauvageot (2000),typical internal span-to-depth ratios for constant-depth girders are between 18 and 22,

$$\frac{l}{h} = 22$$

$$\text{where } l = 100\text{m},\ \ h = ? \qquad \text{(Chen and Duan, 2014)}$$

$$\therefore h = \frac{100}{22} = 4.5\text{ m}$$

The dimensions in Table 3.1 will be used to determine the width of the bridge. With the given composition of the carriageway, the total width of the deck will be calculated as:

Total width of the deck =

$$(2 \times \text{Traffic Lane}) + \text{Hard Shoulder} + \text{Hard Strip} + (2 \times \text{Parapet})(\text{Arethmetic calcculations}) \qquad (3.2)$$

$$\text{total width of the deck} = (2 \text{ x } 3.50) + 3.50 + (2 \text{ x } 0.3) = 12.6\text{m}$$

Two parallel bridges with a width of 12.6m are constructed for the traffic in both directions.

In order to determine the dimensions of the box girder, the total number of segments needs to be estimated. If it is assumed that the hammerhead has a total length of 15m. The first segment has a length of 2m and the other segments are 3m, then the total number of segments that are needed to reach the mid of the span can be calculated as follows:

$$\text{Total number of segments} = \frac{\left(\frac{L}{2} - \frac{L_H}{2} - 2\right)}{3} + 1 = 15 \qquad (3.3)$$

$$\therefore \text{total number of segments} = \frac{\left(\frac{100}{2} - \frac{15}{2} - 2\right)}{3} + 1 = 15$$

Where L = half of the span and L_H = total length of hammerhead

Every segment contains a minimum of 4 prestressing cable. So the minimum number of cable is equal to

$$15 \times 4 = 60$$

For these cables, it is assumed that they contain 12 strands having a nominal diameter of 12.7mm in each strand and thus a nominal area of 98.7mm^2. With this, the equivalent diameter can be calculated from:

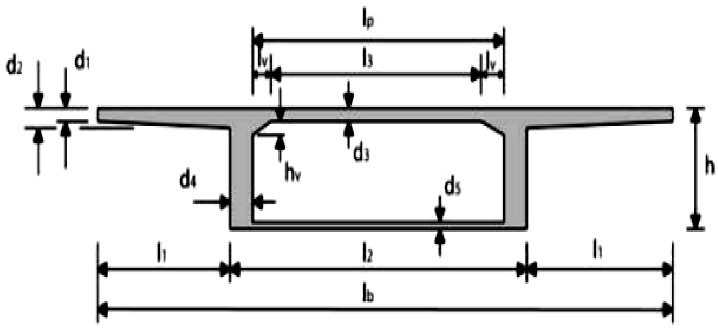
$$\text{Area} = \frac{\pi \emptyset_{eq}^2}{4} \qquad (3.4)$$

$$\emptyset_{eq} = \sqrt{\frac{12 \times 98.7 \times 4}{\pi}} = 38.83$$

The cover that has to be applied can be calculated with $1.5 \times \emptyset_{eq}$ (BS EN 1990 clause 4.4.1.4 and 4.4.1.2 of BS EN 1992-1-1)

$$= 1.5 \times 38.83 = 58.25\text{ mm}$$

$\therefore$ A cover of 60 mm will be used.



3.4b Layout of the box girder bridge

The diagram in Figure 3.4b shows the layout of the cross-section. From the geometrical properties of the box girder, the dimensions for the cross-section near the support are as follows:

$L_b = 12.6m; \quad H = 6.8m;$

$L_1 = 3.1m \left({}^{L_1}/_{L_2} \approx 0.45;\ L_1 \approx 2 \text{ to } 3.5\text{ m} \right)$

$L_2 = 6.4m \left({}^{L_1}/_{L_2} \approx 0.45;\ L_1 \approx 5 \text{ to } 7\text{m} \right)$

$L_3 = L_P - 2$ (3.5)

$= 5.7 - 2 \times 1.2 = 3.3m$

$d_1 = 0.35m$ (Geometric properties of box girder bridge)

This is greater than 0.1m but clearance to the edge of transversal prestressing cables requires more spacing.

$d_2 = 2 \times d_1 \quad = 2 \times 0.35 = 0.7m$ (3.6)

$d_3 = 0.25m$

This is greater than 0.25, enough space for cables in the top part

$d_4 = 0.35m, d_5 = 1m$

$L_P = L_2 - d_2 = 6.4 - 2 \times 0.35 = 5.7m$ (3.7)

$L_V = 0.2L_P = 0.2 \times 5.7 = 1.2m$ (3.8)

$H_V = 0.25m\ (= d_3)$

In the mid-span, the height of the cross section is significantly reduced. For this location it is assumed that H is reduced to 3m and d_5 is reduced to 0.2m.

3.4 Determination of Bending Moment above the Main Support

The point of departure is taken as the construction phase just before closing the mid-span. Assuming a compressive stress of $3N/mm^2$ in the upper concrete fiber as result of dead weight and prestressing only while the compressive stress of 3MPa takes into account the effect of the asphalt layer and traffic load in the Serviceability limit state, as a rule of thumb. The cross-section near the support has an area of $15.44m^2$, while the cross-section at the mid-span has an area of $8.22m^2$. If it is assumed that the concrete has deadweight of $25kN/m^3$, then the bridge has a dead load of 386kN/m near the support and 205.5kN/m at the mid-span. A linear distribution is assumed between these two loads. Figure 3.5 shows the moment and shear force distribution just for closing the bridge (L=50m).

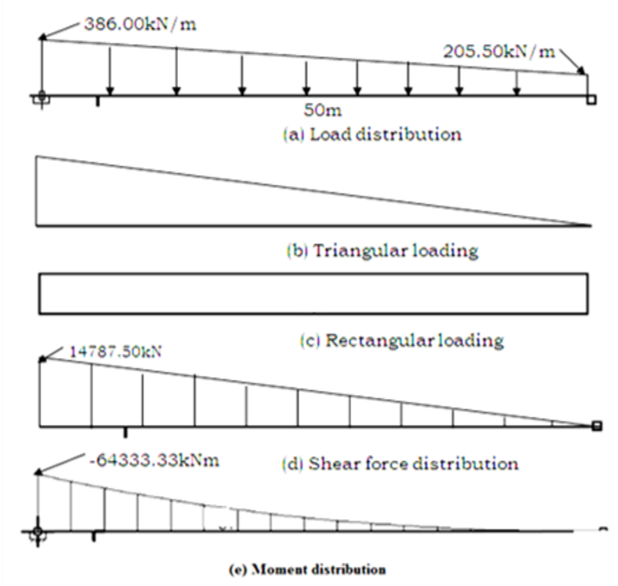


Figure 3.5 Force distribution in the bridge

3.5 Determination of the number of Prestressing Tendons

Assuming a compressive stress of 3N/mm^2 in the upper fiber as a result of dead weight, the first thing to do is to find out how many prestressing force (N) is required to reach this:

$$\sigma_t = -\frac{N \times e}{W_t} - \frac{N}{A} + \frac{M}{W_t} \qquad (3.9)$$

3.6 Design Value for Shear Force

The design value of the shear force is equal to:

$V_d = 1.2V$ ($clause$ 6.2.2 (101) $in\ BS\ EN$ 1992 − 2) (3.10)

Where V = shear force; $V_d = design\ shear\ force, \therefore V_d = 1.2 \times 14787.5 = 17745kN$.

With b = 2 × 0.35 m = 0.7m and

$$d = \mathrm{H} - Cov - \frac{0.07315}{2} \ (BS\ EN\ 1992-2, clause\ 6.2.2\ )(3.15)$$

$$\therefore d = 6.8 - 0.06 - \frac{0.07315}{2} = 6.7m,$$

$$\text{working shear stress is} = \frac{\frac{V_d}{(b \times d)}}{1000} \quad (BS\ EN\ 1992-2, clause\ 6.2.2\ (101)) \qquad (3.16)$$

$$\therefore \text{working shear stress is} = \frac{\frac{17745}{(0.7 \times 6.7)}}{1000} = 3.8\ \mathrm{N/mm^2}$$

The minimum resistance of the concrete section without shear reinforcement can be calculated with the following equation.

$$V_{Rdc} = \left(v_{min} + k1\sigma_{cp}\right)bwd\ (BS\ EN\ 1992-2, clause\ 6.2.2\ (101)) \qquad (3.17)$$

$$v_{min=}\ 1 + \sqrt{\frac{200}{d}} < 2 \quad (BS\ EN\ 1991-1-1, clause 2.4.2.4) \qquad (3.18)$$

$$\sigma_{cp} = \frac{N_{ed}}{A_c} < 7.33\frac{N}{mm^2}(0.2f_{cd}) \ \ (\text{NA to BS EN 1992} - 2, \text{clause 6.2.2 }) \qquad (3.19)$$

With d= 6700 mm (needs to be in mm),

Where $\mathrm{v_{min}} =$ Minimum resistance of the concrete section; $K_1 =$ Stress factor;

$\mathrm{V_{Rdc}} =$ Design shear force; $\sigma_{cp} =$ compressive stress in concrete; $\mathrm{N_{ed}} =$ Axial load;

A_c = Area of concrete and $\mathrm{f_{cd}}$ = Force in concrete (NA to BS 1992 − 1 − 1, clause 2.4.2.2)

K_1 = 0.15 (National Annex to BS EN 1992-2, clause 6.2.2 (101)),

$\mathrm{N_{ed}} = 162298370\mathrm{N}$ and $\mathrm{A_c} = 15440000\ \mathrm{mm}^2$.

$V_{Rdc.}$ can be calculated as 2.27 N/mm^2.

The working shear stress is bigger than the shear resistance, so reinforcement is definitely needed. This shear reinforcement should at least take a shear of between $3.8\frac{N}{mm^2}$ *to* $2.27\frac{N}{mm^2}$.
About 15 segments will be used to reach the mid-span. In total20 cables will be needed, which means that 2 cables will be installed per segment, i.e. (20/15). Not all the cables will have 12 strands. Figure 3.6 shows the alignment of the cables for the bridge when only 3 segments have been installed. In the end, all the $40(2 \times 20)$ cables will pass through the hammerhead, while the last segment at mid-span contains 2 cables.

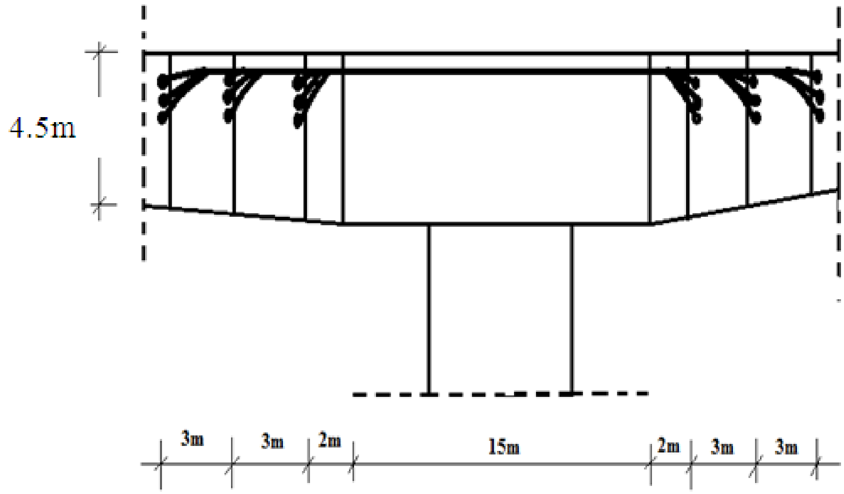


Figure 3.6 Side view of the bridge with respect to prestressing cables

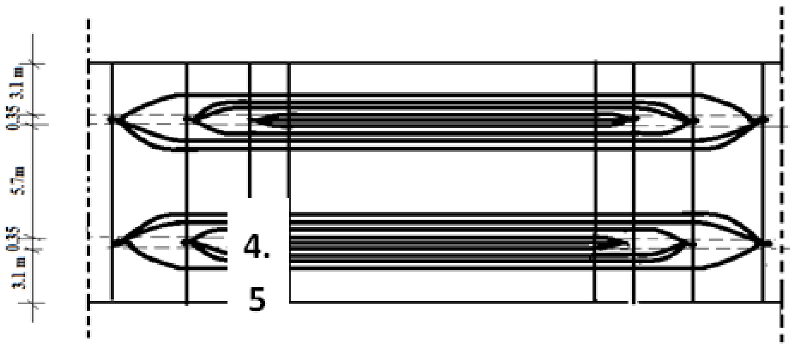


Figure 3.7 Top view of the bridge with respect to prestressing cables

3.7 Design Calculation for the 150mmain span
It is assumed that two separate bridges will be constructed in both directions. To estimate the height of the single cell box girder bridge, the following thumb rules will be adopted:

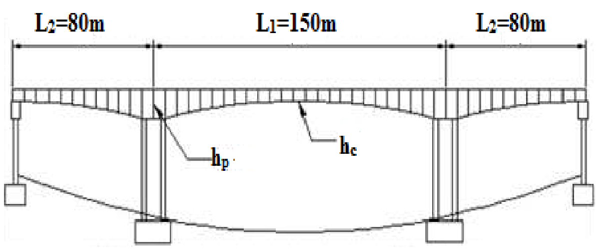


Figure 3.8 Bridge Specification

$\frac{l}{h} = 22$ from Equation (3.1)

Since $l = 150\text{m}, \therefore\ h = \frac{150}{22} = 6.8\ \text{m}$

3.8 Creation of a computer program for the Design of Balanced Cantilever Bridges

BC Bridge is a computer program written in Java Programming language based on the balanced cantilever method. It is written to reduce the time used in the analysis and design of Segmental bridges and has rich graphical interface to aid the user visualized the result of the analysis. Design of balanced cantilever bridges using BC Bridge, is organized into several classes. Using a Unified Modeling Language (UML) diagram, the various packages classes are presented in the next section:

3.9 Package BC Bridge

This package shall contain the main classes which include BCB MAIN, BCB DETAILS, BCB TABLES and BCB GRAPHS

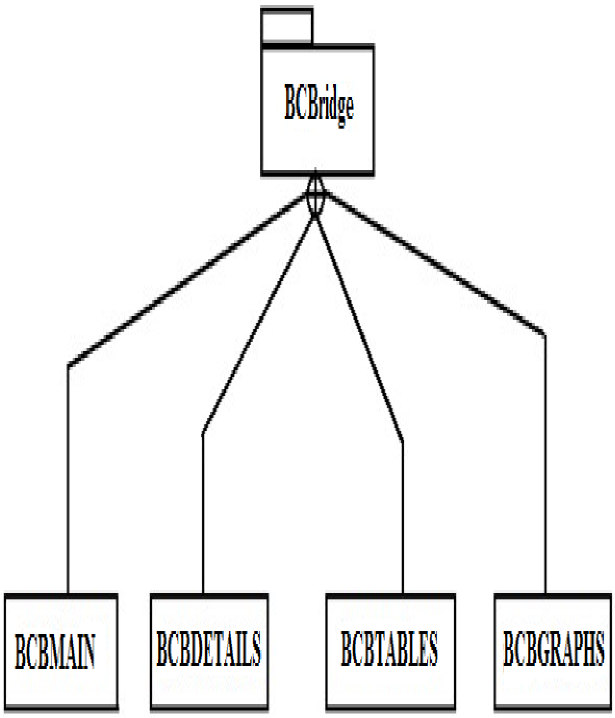


Figure 3.23 Package BC Bridge showing its member classes

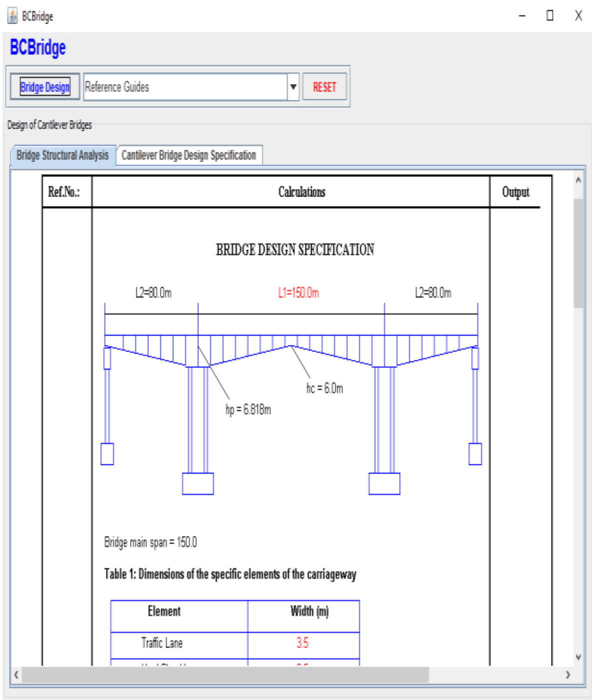


Figure 3.24 The Main Application Window for the developed Computer Program

IV. RESULTS AND ANALYSES

4.1 Manual Analysis and Design Results of Balanced Cantilever Bridge

From the results of the manual analysis and design conducted in chapter three on balanced cantilever bridge design for spans of 100m, 150m, 200m, 250m and 200m respectively, the following results were obtained as shown in Table 4.1 and 4.2

Table 4.1 Results from Manual Analysis (Balanced Cantilever Method)

Main Span Length	Height of Single Cell (h)	Total Segments to mid span	Bending Moment Moment (kNm)	Shear Force(kN)
100	4.5	15	64333.33	14787.50
150	6.8	21	747187.52	22181.25
200	9.1	31	2573333.33	29575
250	11.4	40	4020833.33	36968.75
300	13.64	48	5790000	44362.5

The graphs in figures 4.1 and 4.2 is used to illustrate the design moment and shear force values for cantilever bridges main spans between 100m to 300m. While figures 4.3 to 4.4 shows single cell heights and the number of segments required for the various bridge main spans.

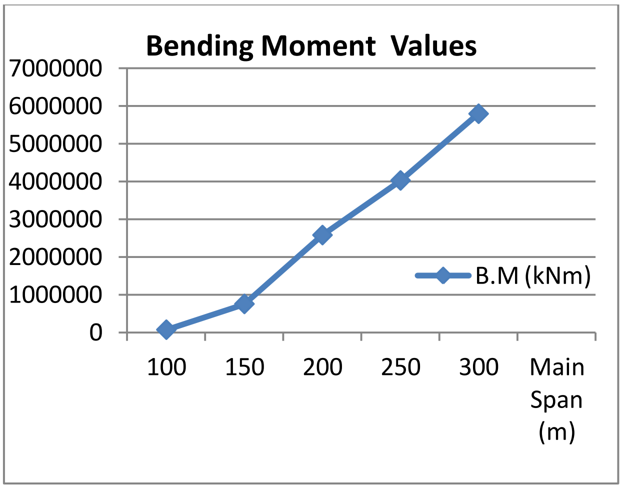


Figure 4.1 Design bending moment values for selected bridge spans

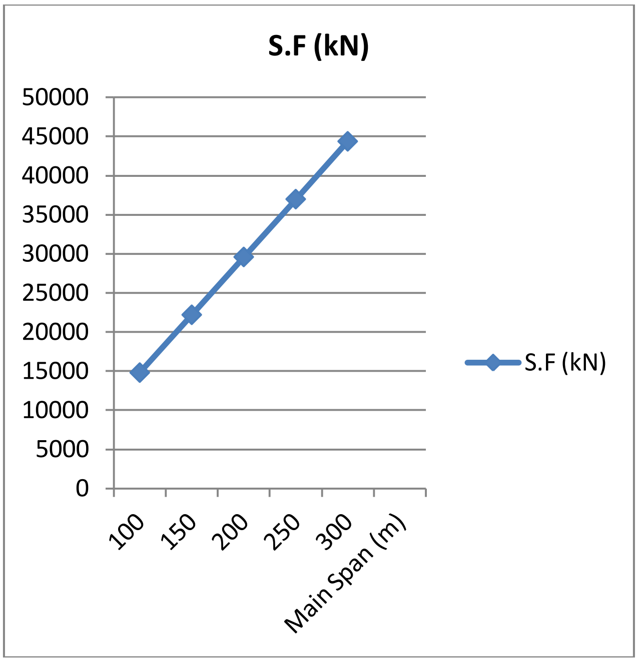


Figure 4.2 Design shear force values for selected bridge spans

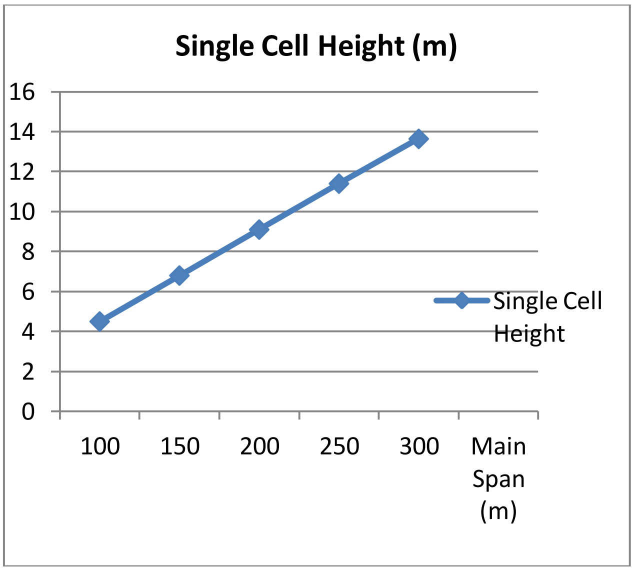


Figure 4.3 Height of single cell for selected bridge spans

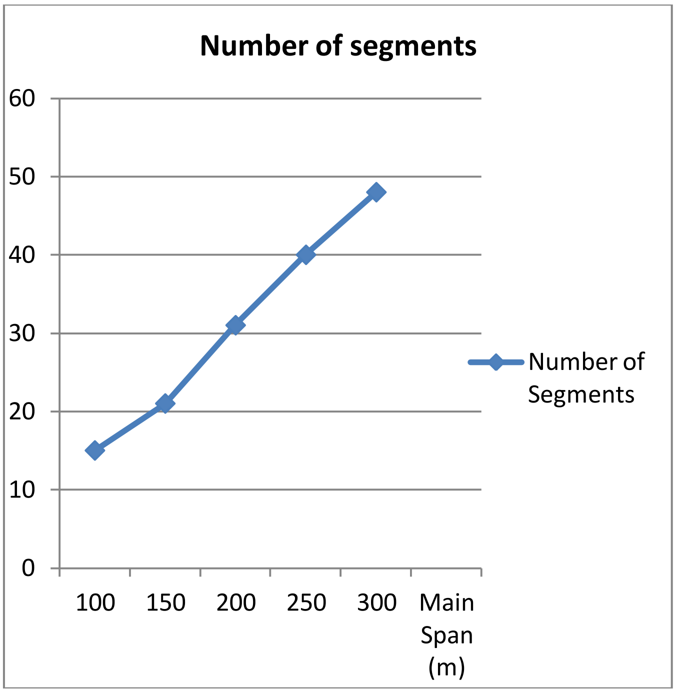


Figure 4.4 Design bending moment values for selected bridge spans

Table 4.2 Results from Manual Design (Balanced Cantilever Method)

Main Span Length	Design Moment (kNm)	Design Shear Force (kN)	Prestressing Force N (kN)	Area of Strands (mm^2)	Number of Strands	Number of Cables
100	64333.33	14787.50	28524.32	24055.93	244	20
150	747187.52	22181.25	162298.37	136874.02	1386.76	116
200	257333.33	29575	520048.16	438581.62	4444	370
250	4020833.33	36968.75	803619.60	677731.06	6867	572
300	5790000	44362.5	1150206.93	970024.82	9822	819

The graphs in figures 4.5 and 4.8 is used to illustrates the prestressing force, area of strands, number of strands and number of cables for balanced cantilever bridges with main spans between 100m to 300m.

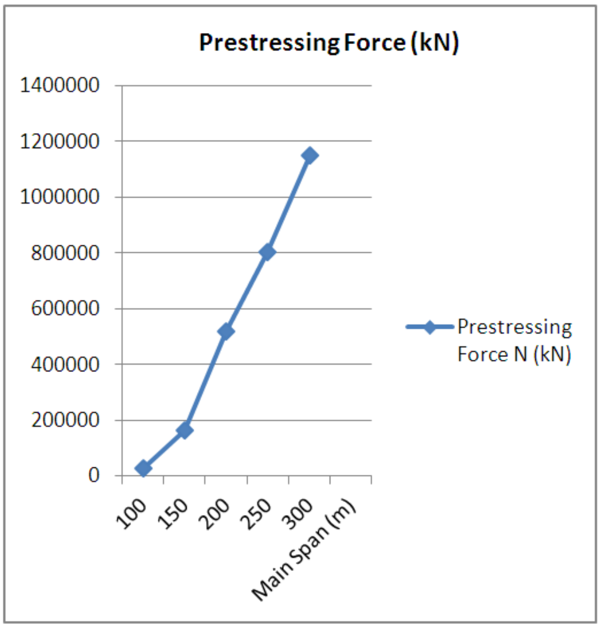


Figure 4.5 Prestressing force values for selected bridge spans

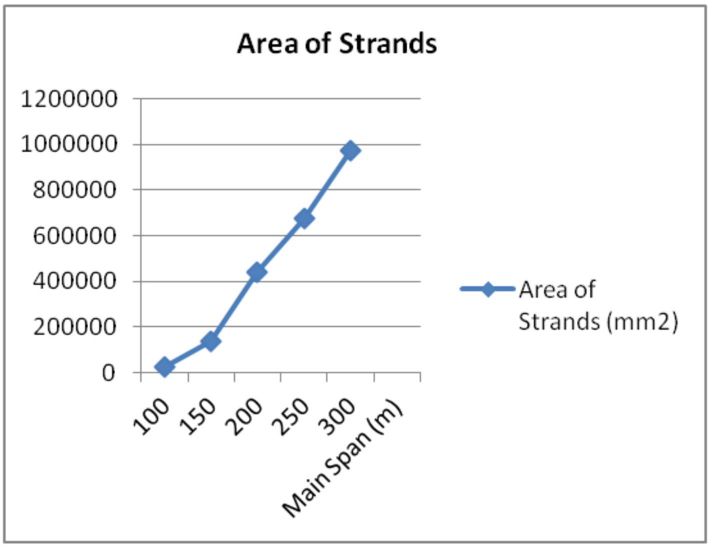


Figure 4.6 Area of strands obtained from selected bridge spans

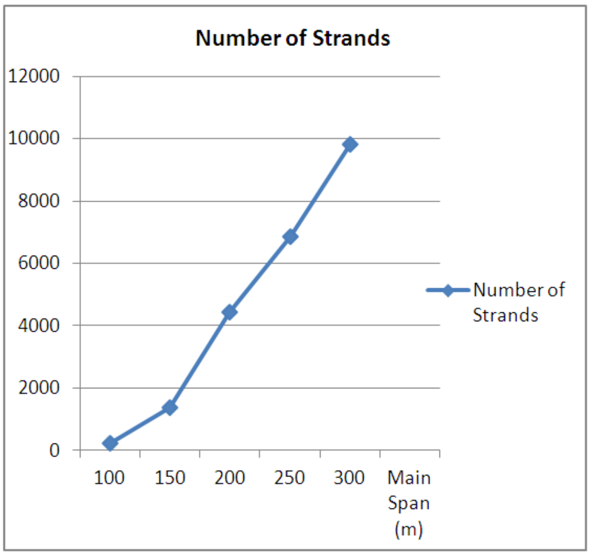


Figure 4.7 Number of strands for selected bridge spans

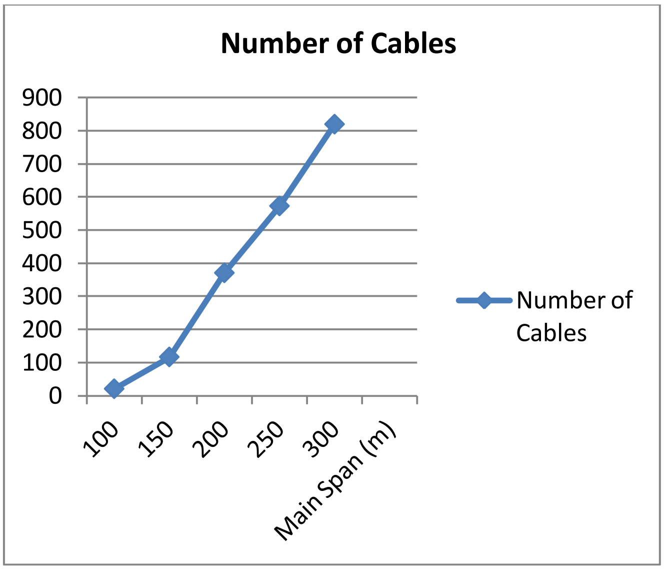


Figure 4.8 Number of cables for cantilever bridge main spans between 100m to 300m

4.2 Computer Program Analysis and Design Results of Balanced Cantilever Bridge

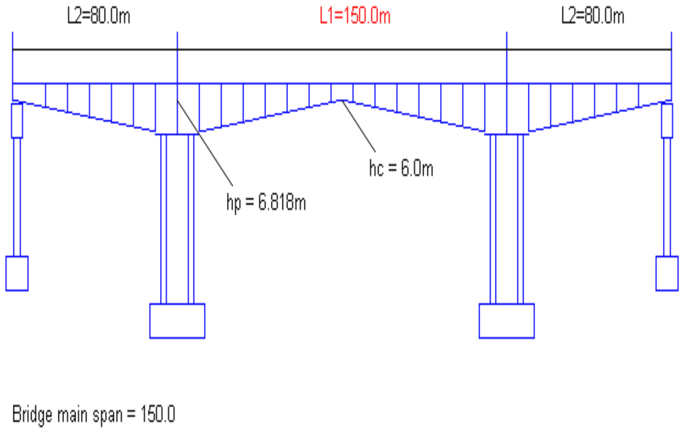


Figure 4.9 Design of Balanced cantilever bridge with 150 main span using computer program

From the results of the computer program analysis and design performed on balanced cantilever bridge design for spans of 100m, 150m, 200m , 250m and 300m respectively, the following results were obtained as shown in Table 4.3 and 4.4

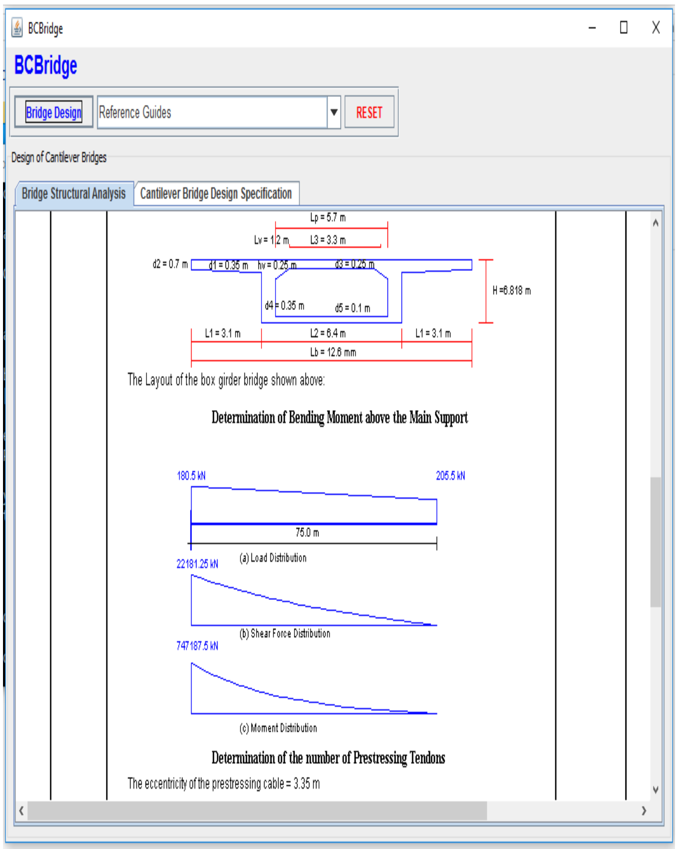


Figure 4.10 Sectional layout of the bridge segment rom the developed computer program

Table 4.3 Results from Computer Program Analysis (Balanced Cantilever Method)

Main Span Length	Height of Single Cell (h)	Total Segments to mid span	Bending Moment Moment (kNm)	Shear Force(kN)
100	4.53	15	64333.30	14787.40
150	6.82	21	747187.48	22181.15
200	9.15	31	257333.33	29575
250	11.4	40	4020833.33	36969.1
300	13.63	48	5790000	44362.5

Table 4.4 Results from Computer Program Design (Balanced Cantilever Method)

Main Span Length	Design Moment (kNm)	Design Shear Force (kN)	Prestressing Force N. (kN)	Area of Strands (mm^2)	Number of Strands	Number of Cables
100	64333.33	14787.50	28524.32	24055.93	244	20
150	747187.52	22181.25	162298.37	136874.02	1386.76	116
200	257333.33	29575	520048.16	438581.62	4444	370
250	4020833.33	36968.75	803619.60	677731.06	6867	572
300	5790000	44362.5	1150206.93	970024.82	9822	819

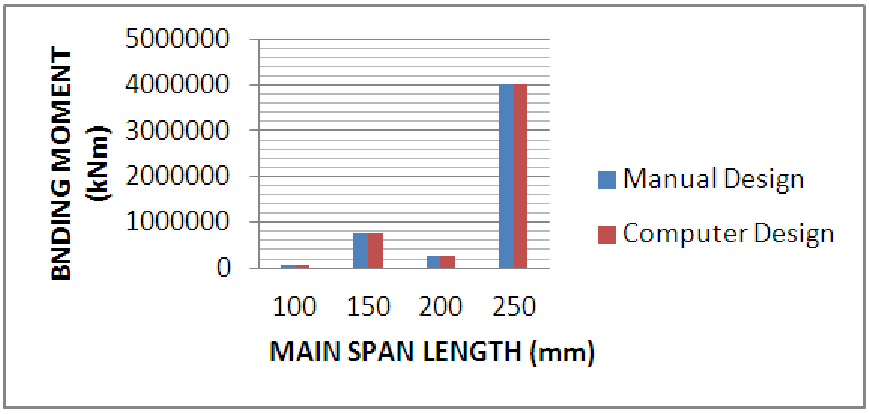


Figure 4.11 A bar chart for design Moments Results for the Manual Design and Computer Program

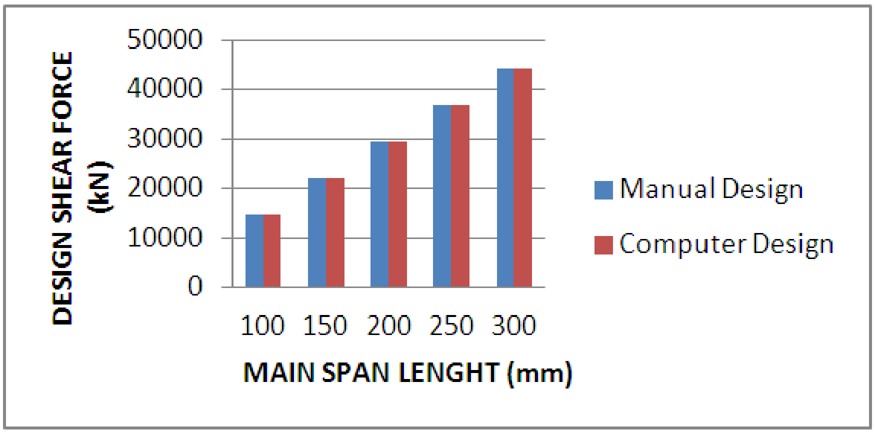


Figure 4.12 A bar chart for the design shear Force Results for the Manual Design and Computer Program

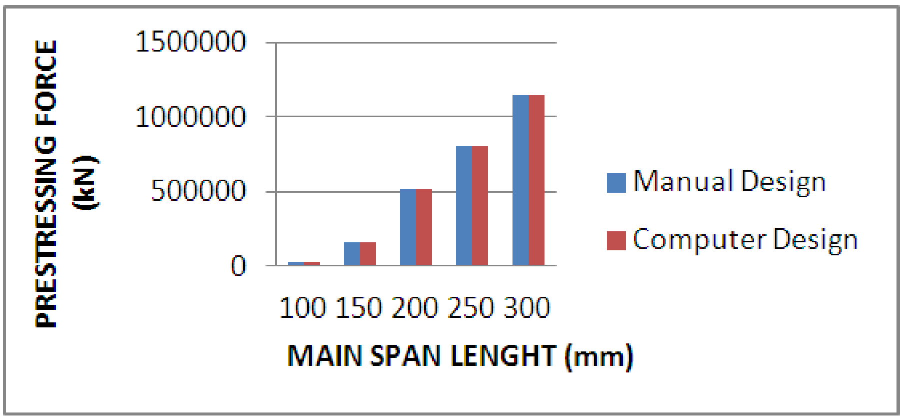


Figure 4.13 A bar chart for Prestressing Force Results for the Manual Design and Computer Program

4.2.2 Comparison of Results between the developed Program and the Manual Analysis

From the tables 4.1, 4.2, 4.3 and 4.4 it can be seen that the results of both analysis and design obtained using manual procedures and computer program are approximately the same. This is due to the fact that the equations used in developing the computer program are the same with the ones used for manual analysis and design of balanced cantilever bridges from Eurocodes BS EN 1992-1-1 and EN 1992-2. Furthermore, the percentage difference results obtain from table 4.5, 4.6 and 4.7 shows very little or no differences between the various results obtain from both manual analysis and computer program analysis. From the results obtained, it showed that the developed computer program has been validated with Eurocodes BS EN 1992-1-1 and EN 1992-2 and can serve as a reliable and handy tool for the analysis and design of balanced cantilever bridges.

5.4 Conclusion

The purpose of this study was to perform analysis and design of balanced cantilever bridges using manual method and developing a computer program for accurate and quick analysis of balanced cantilever bridges. The results obtained from both manual and computer methods includes design moments, design shear forces, prestressing force, area of strands, number of strands and number of cables. All designs were performed in accordance to Eurocode provisions as well as other standard literatures.

This thesis performed manual analysis and design of balanced cantilever bridges. It also developed a Java based computer program for a quick and accurate analysis and design of balanced cantilever bridges. From the results obtained, it shows that the developed computer can serve as a reliable and handy tool for the analysis and design of balanced cantilever bridges.

The Java program is able to design the cantilever cable and continuity cable under loading consider during construction of cantilever bridge and during service. Eurocode can be applied easily by using this Java program which contributes to the design of Cable design based on factors of safety, serviceability, economy and elegance. The Java program also contributes to the performance in terms of suitability and reliability design in the real situation based on construction method.

This study performed the analysis and design of balanced cantilever bridges using manual method and computer program, the bridges was design as a prestressed concrete bridge. Future researcher can perform both manual and

Computer design of steel long span bridges using balanced cantilever method.-

Secondly the computer program developed in this study was mainly written in accordance to Eurocodes. Future works can extend the program to the design of balanced cantilever bridges using other internationally recognized codes for bridge design.

Finally, the developed computer program can be interfaced with standard CAD packages like AutoCAD for generating detailing and working drawing of the balanced cantilever bridge.

The following recommendations are to be follow;

i. For cantilever tendon design, user need to start design by selecting high moment during construction to get maximum prestressing force and maximum number of tendons during construction.

ii. Recommended to place a large number of tendons at beginning of construction phase.

iii. If shear resistance is below the required limit, user can increase web thickness of the box girder can increase shear resistance.

iv. The higher the loading apply on the bridge, the higher the depth of the bridge at the crown needs to be for the same cross section

v. Load model 1 or Gr1a is recommended in design the bridge. Load model 3 or Gr5 is highly not recommended unless the bridge is being designed specifically for special vehicle as it will greatly increase the bridge loading.

vi. Amount tendons and number of segment needed during construction can be decrease by shorten the span of the bridge.

vii. Tendons arrangement in one horizontal straight line. Less tendons will increase the amount of strands inside each particular tendon which depending on the engineer and supply available might be beneficial.

viii. If section is deemed to be inadequate, Increase the depth of the section as the depth greatly affects the section modulus. A single meter can increase the section modulus by up to 25%

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