A Computational Model to Automate the Design of Reinforced Concrete Tee Beam Girder Bridge Using Python Ecosystem

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Abstract. The design of tee beams girder bridge members such as deck slab, main girder, and cross girder is automated by using a computation model based on the python ecosystem. The slab, main girder, cross girder section, and reinforcement detailing are generated by using the purposed computational model. The strength and serviceability checks are as per the Indian Road Congress: 112-2011, Code of Practice for Concrete Road Bridges. The model takes the design parameters of dead and live load from Indian Road Congress 5 and 6 as an input and provides structural detailing of elements involved in the tee beam girder bridge system. The validation of the model architect is performed by comparing it with the solved illustration as per the Indian Road Congress norms. The section sizes and the steel requirement is calculated efficiently and with accuracy thus the time required to generate the structural drawings has reduced drastically. Moreover, with help of the purposed model, a more intensive database of tee beam girder bridges including bridge bearings, piers and foundation can be modelled towards the automation of complete reinforced concrete bridge design as per the Indian Road Congress.

1. Introduction

For national highways, tee beams and slab decks are very common type of assembly used in a bridge design. The system of tee beam deck slab consists of the longitudinal reinforced concrete girder. The lateral rigidity to the deck is provided by the integral continuous deck slab between the tee beams and the cross girders. As per Indian Road Congress (IRC) guidelines, the maximum span of the reinforced concrete tee beams are not more than 30 meters [1]. The total dead load of the girder increases with the larger span resulting in uneconomical sections. In highway crossing, generally, three types of tee beam and deck slab system are used. Type one consists of girder and slab only, in which transverse load distribution is inadequate. Type two is called the girder, slab and diaphragm, in which the magnitude of deflection in a super structure is only 74% that of type one and the magnitude of ultimate load capacity of the superstructure is about 132% that of type one. The overall transverse load distribution is better as compared to type one system. Type three is called the girder, slab, and cross beam type. The magnitude deflection of super structure is about 63% that of type one and the ultimate load capacity of the super structure is about 162% that of type one system. Overall, it is well established that type three tee beam and deck slab system is the best as compared with other two [2]. According to the limit state of design criteria as per IRC-112:2011, all design of the reinforced concrete bridge component must ensure that
the specified life of the bridge structure is not curtailed prematurely due to the attainment of an unsatisfactory condition or limit state [3]. The most common limit state is considered that of strength and serviceability.

In this paper, python programs developed to automate the design of deck slab, main girder and cross girder of two lane simply supported reinforced concrete tee beam girder bridge. Along with the dead load of the members, the tracked vehicle of class A-A loading is used to provide live load on the deck slab. The moment coefficients of Pigeaud’s curves are used to design the deck slab supported on all four sides. The design of main girder and cross girder is performed by using Courbon’s method [4][5][6]. Limit state design as per IRC, 112. 2011 is used in the purposed algorithms. The program performance is validated with the solve illustration as per IRC standards. The programming language such as python helps to express our product requirement by providing language. library packages and python ecosystem for extension packages. The response of reinforced concrete slabs can also be determined by using commercial softwares [7]. In order to use the low-cost response spectrum device (RSDs), python script is used to record the real time accelerometer data and the use it as an input value to determine the response to numerical computations [8]. The libraries such as NumPy and SciPy can easily process and analysis the numerical based on different applications. With help of the python ecosystem, a separate library known as ObsPy (http://obspy.org) for seismology is developed on top of scientific NumPy stack [9].

The overall methodology of the automated design module is shown in Figure 1. The initial input parameters are taken by the user which include the concrete and steel grade, the boundary conditions of each elements and the IRC code provision [10][11]. The design moment (Mu) and the design shear force (Vu) for each members is determined using the input parameters and check for the strength criteria by comparing with the limiting moment of resistance (Mu,lim) and ultimate shear strength (VR.dc). If Mu,lim and VR.dc values are greater than the Mu and Vu respectively, only then serviceability check is performed. Otherwise the changes are made in the area of steel provided and also in the initial input parameters and all the above procedure is repeated again. After the serviceability check is completed, the reinforcement details with the section size is declarer by the algorithm.
2. **Slab Design Sub Algorithm**

The overview of sub algorithm used to design deck slab is shown in Figure 2. Based on the initial data, the depth of the slab is assumed between 200 mm to 250 mm (empirical assumptions). Tentative number of girders are declared by justifying the uniform distribution of girder along the width of the bridge. After calculating the total dead load of the slab including the wearing coat, the design of interior slab panel starts by determining the bending moment (B.M) due to live load and dead load for both spans. The Pigeaud’s curves is used to determine the moment coefficients for B.M. To calculate the moment coefficients (m1 and m2), one wheel of class AA tracked vehicle is placed at the center of the panel and the ratio such as (u/B) and (v/L), which are used in Pigeaud’s Curve, where u, v, B and L are the dimensions of the live load dispersed and the slab panel respectively. The shear force (V) for both live and dead load is calculated. Effective width of slab and load per metre width are determined before dead load shear force calculation using the formula WL/2 where W is the total dead load and L is the effective span between girders. The ultimate design load moment (Mu) and the ultimate design load shear force (Vu) is determined for both live and dead loads. The value of Design Ultimate Bending Moment will be the largest value of either span (long or short span). The design of section is performed by calculating area of steel required (Ast req.) and area of steel provided (Ast pro.), in order to provide adequate diameter and spacing of bars for reinforcement of the slab. The section size and area of steel provided is checked for strength and serviceability. The strength criteria is checked by calculating the Limiting Moment of resistance (Mu lim) with respect to the ultimate design load moment (Mu). The shear strength (VR.dc) is also determined with respect to the ultimate design load shear strength(Vu). The values of Mu lim and VR.dc should be more than the Design moment(Mu) and design shear strength(Vu) respectively. If this holds true, only then serviceability check is performed. But if this condition does not meet, first area of steel provided is revised (step 1) if it still doesn’t pass, the depth of slab is revised (step2) and the whole process is repeated again to determine a new Ast pro. To check serviceability as per IRC 112:201, clause 12.3.4, crack width (Wk) is calculated using maximum crack spacing (Smax), the mean strain in reinforcement under the relevant combination of loads (ɛsm) and mean strain in the concrete between cracks (ɛcm). The value of crack width should satisfy the following equation.

\[
W_k \geq 0.6 \left( \frac{\sigma_{sc}}{E_s} \right)
\] (1)
Where \( \sigma_{sc} \) is stress in the tension reinforcement assuming a cracked section and \( E_s \) is tensile Modulus (Young’s Modulus, Modulus of Elasticity). If the equation (1) is not satisfied, change the area of steel provided and initial input parameters (slab depth) and repeat the whole process. Now for deflection check, three types of deflection are calculated which are due to shrinkage, due to creep and due to live load. These deflections are calculated using values of moment of inertia of cracked section (I_r), effective moment of inertia (I_eff) and moment of inertia of gross section excluding reinforcement (I_gross). If the sum of these three Deflections is greater than the value span/250, then the slab sub algorithm proceed forward with the main and cross girder design; if not then first, Ast provided is revised (step1) if again the requirements are not satisfied, revise the depth of slab (step 2) until all the conditions are fulfilled. After the deflection checks, final area of steel required and with reinforcement steel bar diameter and centre to centre spacing for both short and long span are declared along with the slab section size.

3. Girder Design Sub Algorithm

The sub algorithm for the design of girder is depicted in Figure 3. The Courbon’s method is used for girder design as number of girders are more than three. The reaction factors for the outer girder and inner girder are calculated using values such as dx (distance of girder from the axis of the bridge), moment of inertia(I), and eccentricity(e) i.e., distance between resultant vehicle weight at its CG and Centre line of the bridge width. The slab dead load is transferred to the girder by assuming that the dead load is shared equally by all the girders, therefore the total deck load is divided by the number of girders. The total dead load per meter girder which will be the sum of reaction from deck slab on each girder and weight of (rib)cross girder is calculated. The maximum bending moment at the center of the span is computed by using the above values. Support reaction at either of the supports is calculated which is equal to the maximum shear force at the supports (Vmax). The bending moment in girder due to live load is determined using Influence Line diagram. The impact factor for IRC class AA tracked vehicle, for span 16 m is 10% (impact factor). Bending moment of the main girders (both outer and inner) including impact and reaction factors is calculated. The maximum reaction on each girder (outer and inner) is determined using the track load of Class AA loading vehicle acting on all the girders. This maximum reaction on girders is then used to find out maximum shear force in both outer and inner girders due to live load with impact factor. For calculating design bending moment (\( M_u \)) and Shear Forces (\( V_u \)), first, the total M and total V is computed for outer and inner girder using the formula \( (1.35DL+1.5LL) \). Then, largest value between outer and inner girder for both total M and total V is the maximum design bending moment (\( M_u \)) and shear force (\( V_u \)) respectively. Before calculating Area of Steel Required, the neutral axis depth (Xu) is determined by solving the quadratic equation (2). The value of Xu will help in determining the location of neutral axis, inside or outside the flange. The equation (3) is solved for declaring the area of steel required (Ast).

\[
M_u = 0.36 \times f_{ck} \times b_f \times X_u \times (d - 0.42 \times X_u) \quad (2)
\]

\[
M_u = 0.87 \times f_y \times A_{st} \times d(1 - (A_{st} \times f_y/b \times d \times f_{ck})) \quad (3)
\]

Alternatively, Ast required can be calculated by referring to Table 14 in SPC 16 code, where we will find out the pt value according to the value of \((M_u/bd^2)\), fck and fy. and finally calculate the value of Ast required using equation (4).

\[
pt = 100 \times \frac{A_{st}}{b \times d} \quad (4)
\]
Figure 2. Overview of Sub Algorithm Used to Design Deck Slab
Figure 3. Overview of Sub Algorithm Used to Design Girders
The area of steel provided is calculated in order to provide adequate diameter and spacing of bars for reinforcement of the girders. Next, Check for Ultimate Shear Force is performed. (design of reinforcement for shear). According to IRC 112 2011, the shear strength of concrete section is computed using the following equation (5). The values of VRdc should be more than Maximum design ultimate shear force (Vu), if not then the shear reinforcements have to be designed to resist the balance shear force, for which stirrups are provided and thus the spacing for stirrups is calculated using equation (6).

\[ VRdc = [0.12K(80 \times p1 \times fck)0.33]bw \times d \]  
\[ Sv = (0.87 \times fy \times Asv \times z/VRds) \]

Where z=lever arm to be taken as 0.9d for RCC sections and VRds (i.e. Balance shear force) = (Ultimate Shear Force- VRdc).

Now for check of serviceability, crack width (Wh) using maximum crack spacing (Srmax), the mean strain in reinforcement under the relevant combination of loads (€sm) and mean strain in the concrete between cracks (€cm) is determined by the algorithm. As per the code requirement, the value of crack width must satisfy equation (7). Where σsc is the stress in the tension reinforcement assuming a cracked section as in equation (8). Mu is the Ultimate Design Moment, d is the effective depth, Xu= neutral axis depth and Es= Tensile Modulus (Young's Modulus, Modulus of Elasticity).

\[ Wh \geq 0.6 (\sigma_{sc}/Es) \]  
\[ \sigma_{sc} = Mu/(d - (Xu/3)) \times Ast \]

If the above equation is not satisfied, first change the area of steel provided (step 1) and then again if the check doesn’t pass revise the initial input parameters i.e. slab depth (step2) and the process is repeated until the check is completely satisfied as shown in Figure 3. Now for Deflection Check, three types of Deflection are calculated which are due to shrinkage, due to creep and due to live load. If the sum of these three Deflections is greater than the value span/250(span divided by 250), then we proceed forward with the design. If the deflection check is not satisfied, then the value of Ast provided is revised (step 1). If again the check is not satisfied the value of depth of slab is revised (step2). After these calculations and checks, Final Area of Steel required, and other reinforcement details (diameter of bars and spacing between bars) are calculated. The girder design can also be optimised further once the design prototype is approved [12].

4. Design details
The input file with the data of tee beam girder illustration is shown in Table 1. The grade of concrete and HYSD reinforcement of the concrete is taken as twenty-five and four hundred fifteen newton per millimetre square, respectively. The constant values of Ec and Es are thirty and two hundred gigapascal, respectively. The number of girders that will be provided below the deck slab will be taken as three. More details about the input data are given in the table below.

| S. No. | Description           | Value |
|--------|-----------------------|-------|
| 1      | Carriageway(m)        | 7.5   |
| 2      | Span (c/c of bearing) (m) | 16    |
| 3      | Width of Kerb(mm)     | 300   |
| 4      | Depth of Kerb(mm)     | 600   |
| No. | Description                              | Value |
|-----|------------------------------------------|-------|
| 5   | Thickness of Wearing Coat (mm)           | 80    |
| 6   | Grade of Concrete(N/mm2)                | 25    |
| 7   | HSYD Reinforcement(N/mm2)               | 415   |
| 8   | Value of Ec (Gpa)                       | 30    |
| 9   | Value of Es (Gpa)                       | 200   |
| 10  | No. of girders                          | 3     |
| 11  | Girder Provided at distance (center)(m)  | 2.5   |
| 12  | Width of Main girder in mm               | 300   |
| 13  | Main girder depth in cm                 | 160   |
| 14  | Depth rate per meter Span in main girder(cm) | 10 |
| 15  | Thickness of deck (mm)                  | 212   |
| 16  | Cross Girder provided at every in (meters) | 4  |
| 17  | Cross Girder Breadth(mm)                | 300   |
| 18  | Wheel or Track width(m)                 | 0.85  |
| 19  | Wheel load Contact area along the span in (m) | 3.6 |
| 20  | for live load M1                        | 0.085 |
| 21  | for live load M2                        | 0.024 |
| 22  | Wheel Load of 1 wheel in class aa (KN)   | 350   |
| 23  | k for continuous slab                   | 2.52  |
| 24  | Impact Value                            | 1.25  |

(a). Dead load

| No. | Description | Value |
|-----|-------------|-------|
| 25  | M1          | 0.049 |
| 26  | M2          | 0.015 |

(b). Design of section

| No. | Description   | Value |
|-----|---------------|-------|
| 27  | Clear cover(mm)| 40    |
| 28  | Dia of bars(mm)| 16    |
| 29  | Effective Cover(mm)| 48   |
| 30  | Eccentricity(m) | 1.1   |
31 dx (outer girder) (m) 2.5
32 Parapet Railing (KN) 0.7
33 Mu(max)(KN.m) 1217.504
34 Impact factor 1.1

(c). Calculation of Xu (quadratic equation)

| S. No. | Description          | Value        |
|--------|----------------------|--------------|
| 35     | A                    | 9450         |
| 36     | B                    | -32625000    |
| 37     | C                    | 3913130000   |

(d). Calculating the area of tensile steel required to resist Mu (Ast) (Quadratic Equation)

| S. No. | Description          | Value        |
|--------|----------------------|--------------|
| 38     | A                    | 2.366        |
| 39     | B                    | -516562.5    |
| 40     | C                    | 3913130000   |
| 41     | Pt (for slab)        | 0.689        |

Output values of Deck Slab, Main Girder and Cross Girder are generated by program code using python ecosystem. The output values of the area of tensile steel provided and required for deck slab are found out to be 1340.413 and 1129.96 millimetre square, respectively. The deck slab is provided with sixteen-millimetre bars at a spacing of one hundred fifty millimetres. For main girder, the area of tensile steel (Ast) provided to resist the ultimate design moment is 7822.199 millimetre square and the area of steel provided was calculated to be 7853.982 millimetre square. In the design of cross girder, 10 mm diameter 4-legged stirrups are provided with spacing (Sv) of 76.2987 millimetre. More details about the output values are given below in Table 2.

Table 2. Data Output from the Program

| S. No. | Description                              | Value     |
|--------|------------------------------------------|-----------|
|        | (a). Deck Slab Design Output             |           |
| 1      | Thickness of deck slab (in mm)           | 212       |
| 2      | Required Ast                             | 1129.96 mm²|
| 3      | Diameter                                 | 16 mm     |
| 4      | Spacing assumed                          | 150 mm    |
| 5      | Diameter of steel bars provided          | 16 mm     |
| 6      | Spacing between steel bars               | 150 mm    |
### (b). Main Girder Design Output

|   |   |
|---|---|
| 8 | Width of main girder in mm | 300 |
| 9 | main girder depth in cm | 160 |
| 10 | No. of Girders | 3 |
| 11 | The area of tensile steel required to resist Mu(Ast) | 7822.199 mm² |
| 12 | Provided Ast | 7853.982 mm² |
| 13 | Diameter (assumed) | 25 mm |
| 14 | Clear Cover (assumed) | 150 mm |
| 15 | The Effective Depth (assumed) | 1437.5 mm |
| 16 | Depth of flange (thickness of deck slab) | 212 mm |

### (c). Cross Girder Design Output

|   |   |
|---|---|
| 17 | The area of tensile steel required to resist Mu (Ast) | 445.326 mm² |
| 18 | Diameter (assumed) | 25 mm |
| 19 | No. of bars (assumed) | 4 |
| 20 | Provided Ast | 1963.495 mm² |
| 21 | Spacing of Stirrups (Sv) | 762.987 mm |
| 22 | 4-legged stirrups diameter (assumed) | 10 mm |

### 5. Results

The purposed algorithms in figure 1, 2 and 3 for automation of slab, main girder and cross girder are validated by comparing literature illustration [13] with the output values from the program. Figure 4 and 5 compares the area of steel required in deck slab and girders. The maximum difference between literature values and programming is of 82.96 mm², which is within the limits. Similarly, the design ultimate moment, design ultimate shear force and the ultimate shear strength for all three tee beam girder bridge components are also compared in figure 6,7,8 and 9. The programming values as compared with the literature are within the limits and do satisfy all the design criteria in figure 10 and 11.
Figure 4. Area of Steel Required for Deck Slab (mm2)

Figure 5. Area of Steel Required for Main girder (mm2)

Figure 6. Design Ultimate Moment for Deck Slab (KN.m)

Figure 7. Design Ultimate Moment for Main Girder (KN.m)
6. Conclusion
A Python based algorithm is used to automate the design of deck slab, main girder, and cross girder as the Indian Road Congress guidelines. The program algorithm justifies the design requirements for deck slab, main girder, and cross girder of tee beam girder bridge. Pigeaud’s Curve used for moment calculation in slab performed well using the sub algorithm for slab design. Similarly, Courbon’s method
used for moment calculation provided convincing values in case of girder design. The comparison between the area of steel required and area of steel provided in all three components are within the limits. The serviceability criteria i.e. crack width and deflection are safe. The sub algorithms for slab and girder designs run accurately by providing the number of reinforcement bars and section details as per the literature. This algorithm can further be detailed for dynamic response of the bridge for near faulty conditions.

7. References

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