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Analysis and Design of Wind and Temperature Load of a Continuous Span I-beam Prestressed Concrete Bridge using PBridge Software

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ABSTRACT
This study presents the development of a computer program called "PBridge" for the analysis and design of prestressed I-beam concrete bridges. Prestressed concrete is increasingly used in bridge design worldwide because it can support significant loads and is resilient to the effects of wind and temperature variations throughout its lifespan. The analyses and designs were modelled based on Eurocode design procedures. The bridge model features a continuous-span design with a main span of 40 meters. Each of the two side spans consists of a 7.2-meter carriageway, including two notional traffic lanes of 3 meters each, in both directions. The proposed bridge is expected to span a freshwater river, such as the River Niger in Onitsha, Anambra State, Nigeria. The total initial prestress force of 13770 kN and the total prestress force of 18749 kN were derived using 96 strands for the continuous-span prestressed bridge for both manual calculations and PBridge results. The selected prestressed strands, Y1860S7G with a diameter of 12.7 mm (7-wire drawn strands), were found to be adequate for this continuous span. To further validate the results, the bending moment and shear force outcomes from both STAAD Pro and PBridge were compared for the continuous span. The percentage difference for the bending moment was 0.0044 at a distance of 5 meters from the end support, while for shear force, it was 0.0034 at the same distance. These findings indicate that the developed program can be reliably used for the analysis and design of prestressed concrete bridges.

KEYWORDS: **PBridge, computer program, prestressed concrete, I-Beam, bridge**

I INTRODUCTION

The advent of computer programming has significantly advanced the development of numerical methods, facilitating easier solutions in the analysis and design of civil engineering structures. These methods rely on iterative computations to approximate solutions. Given the complex and often cumbersome nature of analytical methods used in bridge analysis and design, the adoption of numerical methods becomes essential as they provide a viable alternative to traditional analytical solutions. In this context, the structural Eurocodes [1, 2 & 3] promote greater economic efficiency in design compared to many existing codes of practice. They lead to more cost-effective constructions and offer fewer restrictions than BS 8110. Additionally, these codes are logically structured to minimize duplication [4].

The inadequacy of civil infrastructure has emerged as a significant social and economic issue in Nigeria. The ability of a modern society to thrive economically and socially is heavily reliant on well-designed and constructed civil infrastructure. Currently, Nigeria possesses a markedly lower number of bridges than is required to support efficient transportation and economic sustainability [5]. Research conducted by Täljsten [6] on the challenges associated with prestressed concrete bridges, particularly as they approach the end of their service life, highlights that these structures can undergo a range of deteriorating processes. Examples of defects and inadequacies include cracking, corrosion, voids, bond loss, reduced cover layers, delamination, fatigue, and loss of stiffness and strength.

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Addressing these challenges necessitates the implementation of appropriate design and evaluation techniques to avert problems that could compromise structural integrity or shorten service life.

Furthermore, the processes of analyses and design of bridges are time-consuming, tedious and technically prone to errors. The necessity for effective techniques and instruments to plan, build, and oversee this enormous asset base is becoming increasingly apparent to the structural and bridge engineers. Hence, the need to resort to computer programming methods, as done in this work.

1.2 Previous works on bridge design using computer applications

A lot of research work has been carried out using computer programs. Using the finite element method, Gupta [7] conducted a thorough analysis of box girders with three distinct cross sections: circular, trapezoidal, and rectangular. These box girders were subjected to a linear analysis using SAP2000. To analyze the intricate behaviour of the various box girders, they utilized a discretized domain with three-dimensional, four-noded shell elements. A comparison of the box-girder and T-beam girder superstructures was done by Saxena and Maru [8]. Comparing results from manual and computer methods (Java programs and commercial finite element programs like STAAD-PRO) was the aim of the study. A study on the design and cost analysis of pre-stressed concrete girders was conducted by [9]. The study presented two analyses of balanced cantilever bridges: one using a Java program, and the other by manual method. The results were compared with those acquired using the STAAD PRO program for the same task. The amounts of steel and concrete needed for each girder were calculated. Pre-stressed concrete box girder design and analysis were the subject of a study conducted by [10]. She examined the deflections, stress criteria, and different span/depth ratios to determine the most advantageous locations for pre-stressed tendons.

Garg and Kumar [11] reviewed several studies on box girder conducted over the years, including the creation of thin-walled beam theory and curved beam theory. Pre-stressed tendons were added, and a thorough analysis of a bridge section was conducted. The loading was carried out using SAP2000 software. The stress tendons were added to bridge sections at various positions in different combinations. [12] examined how a box beam girder behaved in a pure torsion situation. He discussed several techniques for fortifying concrete box beams against torsional stresses. In their work, they used two distinct horizontal and vertical directions to experimentally strengthen the box beam using the external pre-stressing technique. Additionally, a computational process was created to forecast the box beams' torsional capacities under torsion, and the outcomes were contrasted with the experimental ones.

Umeonyiagu [13] used both manual and computer methods to conduct research on the analysis and design of detailed balanced cantilever bridges in accordance with Euro codes. Only the superstructure, which serves as a load-bearing member and constitutes the dynamic element, was taken into account during design. Additionally, a Java-based computer program was created to study, plan, and create the balanced cantilever bridge. The balanced cantilever method of designing prestressing cables for box girder bridges was the main focus of the Java program. Techniques for visualization and algorithms were employed by the program. This Java program makes it simple to apply the Eurocodes BS EN 1992-1-1 and EN 1992-2 for designing cables that take into account safety, serviceability, economy, and elegance. The suitability and dependability of the Java program also contribute to performance. It also provides balanced cantilever bridge design and analysis in a timely and accurate manner.

II MATERIALS AND METHOD

2.1 Prestressing Materials

Concrete: Prestressed concrete requires concrete with a relatively higher tensile strength than regular concrete and a high compressive strength at a reasonable age. Portland cement, water, admixtures, and fine and coarse aggregates make up the air-entrained concrete for the members. Either air-entraining Portland cement or an authorized air-entraining admixture can be used to achieve the air-entraining feature. The percentage of entrained air must not be less than 4 percent nor greater than 6 percent. Minimum cement content of 300 to 360 kg/m^3 is prescribed for the durability requirement. The water content should be as low as possible.

Anchorages: A prestressing system called anchorages is found at the end of a section with a high tensile strength. These anchors act as locks on both ends once the wires are stressed. Large, resilient bulkheads support these anchorages, which in turn support the extremely high concentrated forces applied to each tendon [14].

Jacking Systems: The jacking system, or the process by which the prestressing force is transmitted to the steel tendons, is one of the essential elements of a prestressing operation. Hydraulic jacks with a capacity of 10 to 20 tons and a stroke of 6 to 48 inches are used to apply this force, depending on whether post-tensioning or pretensioning is being used, as well as whether individual tendons are being stressed simultaneously or individually [14].

Strands and Bars: Steel wire with a high tensile strength is used to make the post-tensioning strand. Six of the seven wires that make up a strand are helically wound to a long pitch around a central wire known as the "king" wire. According to ASTM [15] all strands must be Grade 1860 MPa (270 ksi) low relaxation seven-wire strands. However, 32mm (1-1/4in) or 35mm (1-3/8in) diameter bars are usually used for post-tensioned bridges due to their ease of handling, installation, removal, and re-use in typical applications.

Wedges and Strand-Wedge Connection: Proper strand anchoring depends on the wedge performance. Since various wedges have been created for specific systems and applications, there isn't just one typical wedge. However, the following qualities should be present in wedges for post-tensioning systems, a minimum of 2.5 times the strand diameter for the wedge length, a 5–7 degree wedge angle, internally positioned serrated teeth for holding the thread, steel alloys or low carbon case-hardened, and a groove around the thick end of two or three pieces that have an o-ring or spring wire retainer clip, to bite into the strand and conform to the irregularity between the strand and wedge hole. Wedges are case-hardened with a ductile core.

Ducts: The post-tensioning tendon steel is subsequently placed in a continuous void created by ducts through the concrete. The duct's potential function as a barrier to corrosive agents received little consideration at first. The duct's quality, continuity, and integrity are now highly valued because they act as a natural corrosion barrier.

Strand Tendons: The inside cross-sectional area of the duct is standardized to be at least 2.5 times the net area of the strand tendon cross-sectional area [16]. Oval "flat" ducts are frequently utilized for transverse tendons in concrete box girder deck slabs. Some systems can accommodate up to five strands, but typically these transverse tendons are composed of up to four strands with a diameter of 0.6 inches. An oval duct's internal clear dimensions must be at least 25 mm (1 in) vertically and 75 mm (3 in) horizontally.

Bar Tendons: Tendons with a single post-tensioning bar ought to have an internal duct diameter that is at least 12 mm (½ in) bigger than the bar or bar coupler's maximum outside dimension. In some cases, a higher clearance might be required or preferred. Some applications for this would be to accommodate bridges with slightly curved alignments or to give greater tolerance for temporary bars.

Corrugated Steel Ducts for Tendons: Corrugated steel ducts are made from strip steel that has a minimum wall thickness of 0.45mm (26-gauge) for ducts smaller than 66mm (2-5/8 in) in diameter or 0.6mm (24-gauge) for ducts larger than that. The steel is spirally wound to the required diameter. Strip steel needs to be coated with G90 coating weight. To maintain the proper profile between supports when concrete is being placed, corrugated steel ducts should be manufactured with welded or interlocking sufficiently rigid seams, corrugated steel ducts must be flexible enough to bend without crimping or flattening.

Grout: Grouting is the process of filling a duct with a substance that creates a strong bond between the tendon and the surrounding grout while also giving the prestressing steel an anticorrosive alkaline environment. Grout primarily consists of cement and water, with a ratio of roughly 0.5; additional ingredients include pozzolans, expansion agents, and some admixtures that reduce water content.

2.2 Bridge Design Specifications

The Eurocode-designed composite prestressed concrete bridge is envisioned to traverse a freshwater river, such as the River Niger in Onitsha, located in Anambra State, Nigeria. The bridge features a main span of 40 meters and is designed for continuous spanning. Additionally, the proposed structure includes two side spans with a carriageway measuring 7.2 meters, accommodating two hypothetical traffic lanes of 3 meters each in both directions. The specific dimensions of the bridge elements are detailed in Table 1.

Table 1 Design Assumptions of continuous span bridge

Span length	40.0m
Beam type	Post-tensioned I Beams
Beam Spacing	2.0m
Deck width	12.4m
Carriageway width	7.2m
Concrete grade for the beam	C50/60
Concrete grade for the slab	C40/50
Cement grade	42.5
Average wind speed of the site	18km/h
The basic wind speed of the site Vb	5m/s
Density of air	1.25kg/m3
The bottom of the bridge deck above the ground	7m

2.3 Wind analysis and design

2.3.1 Bridge parameters

The bottom of the bridge deck = 7.0m above the ground floor

Category = Category III area

The average wind speed of River Niger in Anambra State is 18km/h (5 m/s), $V_{b,0}$ = 5 m/s

For the mean wind velocity $V_m(z)$, the equation is defined in Equation (1a) and $C_r(z)$ is defined in equation (1b) and (1c).

$$V_m(z) = C_r(z) \,.\, C_o(z) - V_b \tag{1a}$$

$$C_r(z) = k_r . In(z/z_o) for\ z_{min} \leq z \leq z_{max} \tag{1b}$$

$$C_{r(z)} = C_r . (z_{min}) for\ z \leq z_{min} \tag{1c}$$

Where

z_o is the roughness length

K_r is the terrain factor depending on the roughness length Z_o calculated using

$K_r = 0.19(z_o/z_{o,II})^{0.07}$

2.3.2 Wind Turbulence

The turbulence intensity $I_v(z)$ is given by Equation (2a) and (2b)

$$I_v(z) = {}^{\sigma_v}\!/_{V_m} = {}^{k_i}\!\Big/\left[C_{o(z)} . In\left(\frac{z}{z_o}\right)\right] \tag{2a}$$

for $z_{min} \leq z \leq z_{max}$

$$I_v(z) = I_v . (z_{min}) \tag{2b}$$

$for\ z \leq z_{min}$

Where k_i is the turbulence factor of which the recommended value is 1.0

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C_o is the orography factor described above

Z_o is the roughness length described above

2.3.3 Peak Velocity Pressure

Peak velocity Pressure is given by the expression in equation (3)

$$q_p(\mathrm{z}) = [1 + 7 \,.\, I_v(z)]\; 0.5\mathrm{p}\; V_m^2(\mathrm{z}) = C_e(\mathrm{z}).\, q_b \tag{3}$$

The wind force in the *x*-direction can be found using Equation (4) in cases where it has been determined that a dynamic response approach is not required.

$$F_w = \frac{1}{2}.\rho.v_b^2.C.A_{ref,x} \tag{4}$$

Where:

ρ is the density of air,

v_b is the basic wind velocity,

C is the wind load factor for bridges,

$A_{re*f,x}$ is the reference area.

The reference area $A_{ref,x}$ for decks with plain beams or webs without traffic should be defined as given in Equation (5):

$$A_{ref,x} = d_{tot}.L \tag{5}$$

Where $d_{tot} = d + d_1$ is defined according to the terrain parameters of the bridge; L is the length of a span of the bridge deck.

2.4 Thermal Stress Parameters

The compressive stress σ due to restraining the expansion arising from temperature changes ΔT is given by equation (6).

$$\sigma = -\alpha_T \times E_{cs} \times \Delta T \tag{6}$$

Where

$\alpha_T =$ Coefficient of thermal expansion

$E_{cs} =$ Young's modulus

$\Delta T =$ temperature change

Taking the moment about the soffit, the first moment of area is given by equation (7)

$$M = A_c \times Y_c \tag{7}$$

For the forces F in different segments of the cross-section, it is obtained using equation (8).

$$F = Average\ stress\ \times Area \tag{8}$$

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The resultant of the restraining stress distribution shown in Tables 1 and 2 for the heating and cooling sections of the bridge is at a distance *C* from the top. The value of *C* is determined using equation (9). Figure 1 presents the position of the resultant stress distribution.

$$C = \frac{D}{3} \times \frac{2\sigma_{bottom} + \sigma_{top}}{\sigma_{bottom} + \sigma_{top}} \tag{9}$$

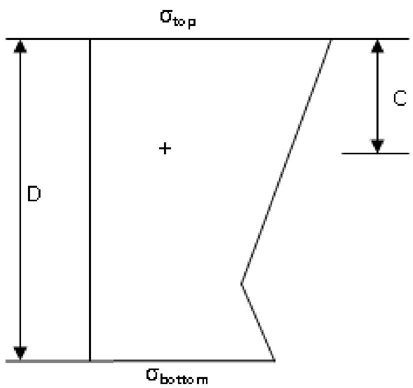

Figure 1 Position of the resultant stress distribution

Table 1 Restraining Stresses in the Continuous span Cross Section: Heating

Level from top mm	Ec, GPa	ΔT°C	σMPa
0 (slab)	35	13	-4.55
130 (slab)	35	4.3	-1.51
150 (slab)	35	3.0	-1.05
300 (slab)	35	2.0	-0.70
150 (key)	37	3.0	-1.11
250 (key)	37	1.8	-0.67
300 (key)	37	2.0	-0.74
300 (beam web)	37	2.0	-0.74
600 (beam web)	37	0	0
1800	37	0	0
2480	37	2.5	-0.93

Table 2 Restraining Stresses in the Continuous Span Cross Section: Cooling

Level from top (mm)	E_c (GP_a)	ΔT(°C)	σ(MP_a)
0(slab)	35	-8.4	2.94
150 (slab)	35	-4.7	1.65
300 (slab)	35	-0.5	0.18
150 (key)	37	-4.7	1.73
300 (key)	37	-0.5	0.19
300 (beam web)	37	-0.5	0.19
620 (ΔT_2)	37	-1.0	0.37
1800	37	-3.5	1.30
2480 (soffit)	37	-6.5	2.41

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2.5 Development of the PBridge Software

The software, known as "PBridge," is a standard desktop application designed for the analysis and design of prestressed concrete bridges. For optimal performance on Windows, the application requires Java Runtime Environment (JRE) version 1.5 or higher. Java is a class-based, object-oriented, high-level programming language characterized by minimal implementation dependencies. The complex process of coding is made more accessible through a visual reference using the Unified Modeling Language (UML). UML is a standardized visual modeling language in software engineering that provides a versatile, flexible, and user-friendly approach to visualizing system design. Figure 2 illustrates the input interface of the UML utilized to model the PBridge software. This input window allows users to enter the basic parameters of the bridge based on existing data, after which they can click "OK" to execute the design.

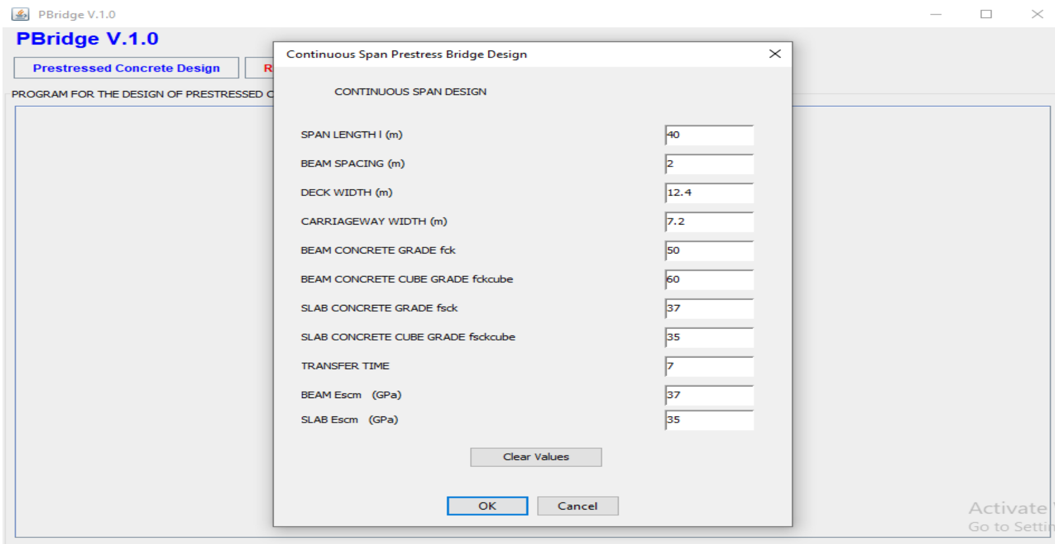

Figure 2 Input window of the developed PBridge software

III RESULTS AND DISCUSSION

3.1 Resultant effect of wind load, heating and cooling on the bridge

The impact of wind load on the bridge is depicted in Figure 3. The wind intensity of 0.054 kN/m² was calculated using equation (4) based on the average wind speed recorded in Onitsha, Anambra State, Nigeria. The wind load was applied uniformly across the bridge and typically exerted in a horizontal direction. Variable temperature effects resulting from both heating and cooling are illustrated in Figures 4 and 5, respectively. It was noted that the heating effects were more pronounced towards the upper part of the bridge, with the highest heating effect of 1.89 MPa occurring at a distance of 600 mm from the top surface. Conversely, the lowest heating effect of -0.42 MPa was observed at a distance of 2480 mm at the soffit point of the bridge, indicating that as the elevation decreases, the temperature heating effect also diminishes.

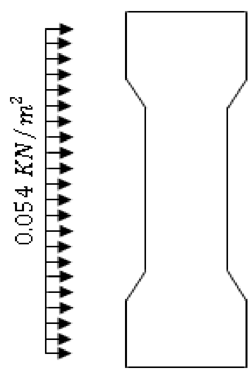

Figure 3 Resultant effect of wind load

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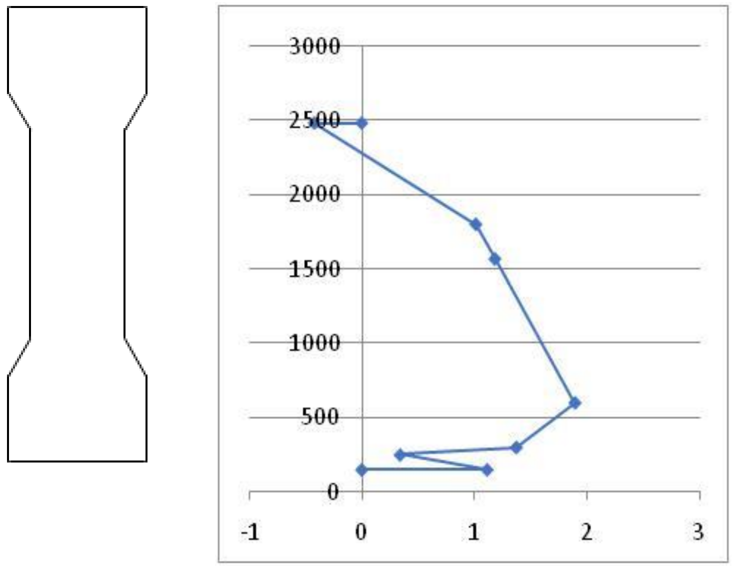

Figure 4 Resultant Stresses due to Heating

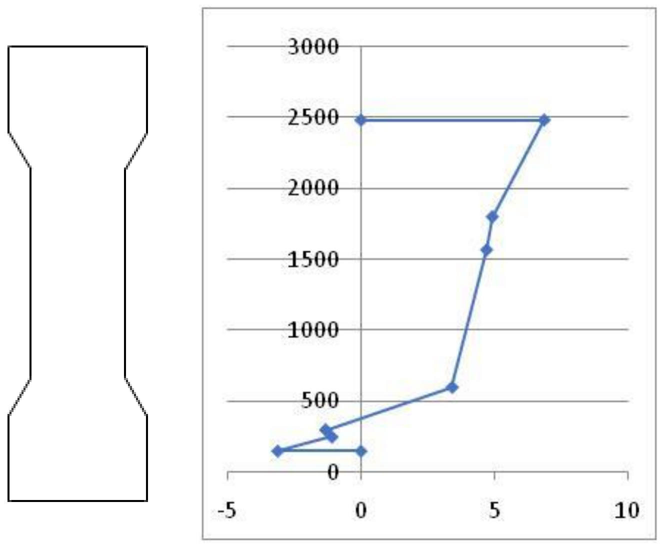

Figure 5 Resultant Stresses Due to Cooling

3.2 Design Result from the Computer Programme

The results generated by the computer program for the continuous prestressed I-beam concrete bridge are presented in Figure 6. The program interface displayed a sketch of the bridge section along with detailed specifications of the design. The essential data for the PBridge program was compiled using parameters derived from the manual calculation formulas, and the design outcomes align closely with those obtained through manual calculations.

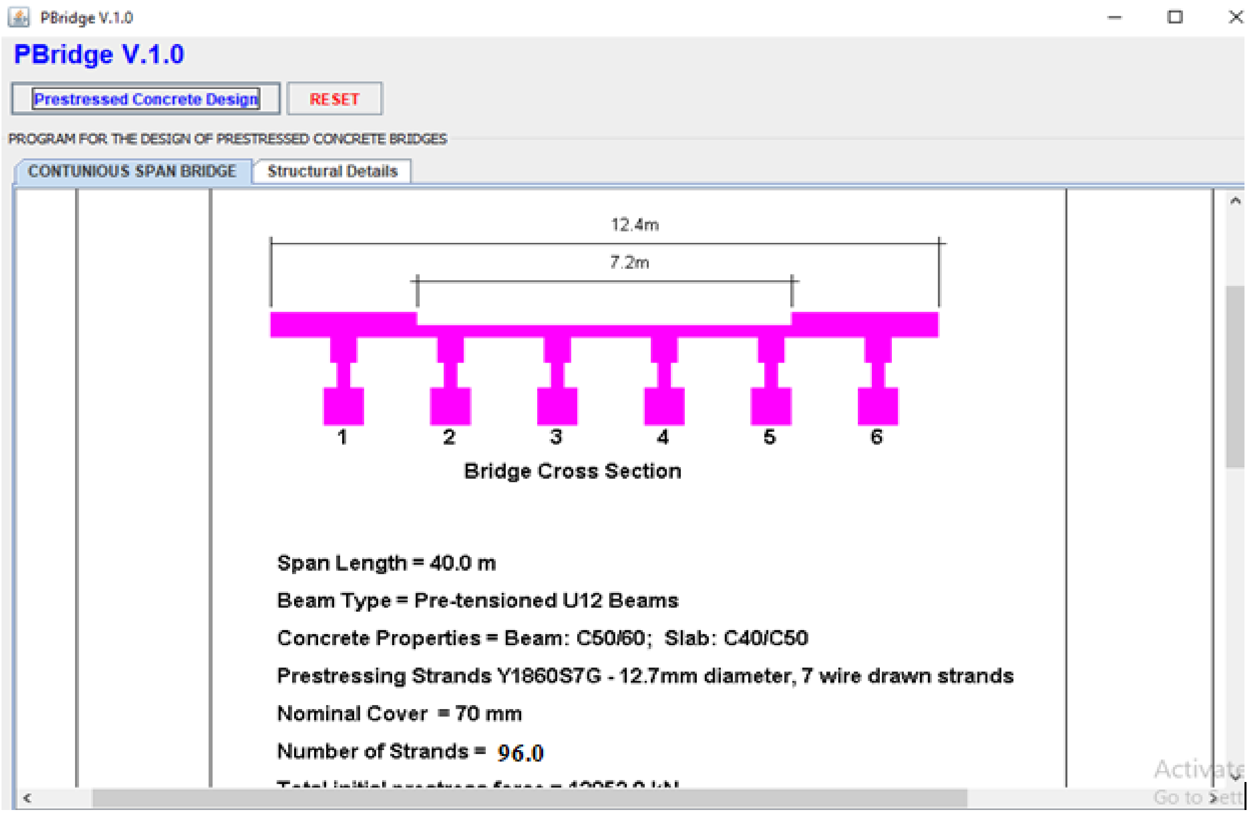

Figure 6 Interface of the PBridge developed a programme for continuous span.

The details of the continuous beam design are summarized in Table 3, the values obtained are in accordance with the stipulations in BS EN 1992-1-1. The summary of the materials and schedules are presented in table same table 3.

Table 3 Design details of the continuous beam

Span Lengths	40.0 metres each
Beam type	Post-tensioned I Beams (adjusted)
Concrete Properties	Beam: C50/60, Slab: C40/50
Prestressing Strands	Y1860S7G – 12.7mm diameter, 7 wire-drawn strands
Nominal cover	70 mm
Number of strands	96
Total initial prestress force	13770 kN
Total prestress force	18749 kN
Eccentricity at support	-395mm
Eccentricity at midspan	116mm
Ducts	60mm diameter, 7 strands in each
End Block Reinforcement	Individual anchorages - six 14mm closed links, distributed over 200mmAll anchorages - fifty-five 16mm closed links, distributed over 2400mm

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3.3 Bending Moment and Shear Force

To further validate the authenticity of the obtained results, the Bending Moment outcomes for both STAAD Pro and PBridge were compared in Table 5 for the continuous span. The percentage difference observed was 0.0044 at a distance of 5 meters from the end support. This indicates that the developed program can be reliably used for the analysis and design of prestressed concrete bridges. Moreover, the moment values align with the recommendations set forth by the Eurocodes, ensuring that the design is satisfactory.

Table 4 Bending Moment and Shear Force for Continuous span

Bridge Type	**Distance (m)**	M_{pimp} **(kNm)**	M_{nimp} **(kNm)**	V_{Ed} **(kN)**
Prestressed concrete bridge(Continuous)	0	0	0	1113.145
	5	4042.821	-680.977	766.869
	10	6555.943	-1048.822	421.593
	15	7797.922	-1595.501	75.317
	17.4	7903.044	-1736.555	1.233
	20	7711.999	-2135.873	74.295
	25	6409.988	-2794.900	434.622
	30	3960.899	-3589.611	785.665
	35	982.599	-4836.111	944.322
	40	-2376.920	-7446.012	1221.314

3.4 Comparison of the results

To further validate the authenticity of the obtained results, the Bending Moment outcomes for both STAAD Pro and PBridge were compared in Table 5 for the continuous span. The percentage difference observed was 0.0044 at a distance of 5 meters from the end support. This indicates that the developed program can be reliably used for the analysis and design of prestressed concrete bridges. Moreover, the moment values align with the recommendations set forth by the Eurocodes, ensuring that the design is satisfactory.

Table 5 Percentage Difference of Bending Moment for the Continuous Span

	StaadPro		**PBridge**		**Percentage difference**	
Distance (m)	M_{pimp} (kNm)	M_{nimp} (kNm)	M_{pimp} (kNm)	M_{nimp} (kNm)	M_{pimp} (kNm)	M_{nimp} (kNm)
0	0	0	0	0	0.0000	0.0000
5	4043	-681	4042.821	-680.977	0.0044	0.0034
10	6556	-1049	6555.943	-1048.822	0.0087	0.0170
15	7798	-1596	7797.922	-1595.501	0.0010	0.0313
17.4	7903	-1737	7903.044	-1736.555	-0.0006	0.0256
20	7712	-2136	7711.999	-2135.873	0.0000	0.0059
25	6410	-2795	6409.988	-2794.900	0.0002	0.0036
30	3961	-3590	3960.899	-3589.611	0.0025	0.0108
35	983	-4836	982.599	-4836.111	0.0408	-0.0023
40	-2377	-7446	-2376.920	-7446.012	0.0034	-0.0002

IV CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The study clearly demonstrates the significance of the development of the computer program "PBridge," designed to simplify the complexities involved in designing prestressed concrete bridges.

PBridge effectively aids designers by offering a set of load models that are calibrated to account for the impacts of traffic, wind, and temperature loads, as outlined in the Eurocodes, which encompass various potential actions on structures. This advancement represents a remarkable step forward in the field of engineering.

It is important to note that computer programs operate based on coded data; therefore, the accuracy of this data directly influences the quality of the results obtained. The expertise of the designer plays a crucial role in achieving an effective and economical design. During the iterative design process for prestressed concrete, numerous preliminary assumptions regarding the aforementioned variables must be made. If any of these assumptions are found to be incorrect, the designer must revisit and adjust all prior calculations. An experienced designer can arrive at a successful design solution more efficiently, as they are able to make well-informed decisions throughout the process.

4.2 Recommendation

i. Future research is recommended on the development of computer programs for designing metal or variable-concrete composite sections, in addition to prestressed concrete. This research should focus on determining section properties and incorporating two different concrete strengths. An effective area should be established for either the slab or the beam, considering the differences in moduli of elasticity.

ii. Furthermore, the computer program developed in this study is currently Java-based. Additional research should explore alternative aspects of computer program development.

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