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SOFTWARE DEVELOPMENT FOR DESIGN OPTIMIZATION OF PRESTRESSED CONCRETE BEAMS

Amr A. Abd El-Rahman [1], Khaled M. Hilal [2], Ahmed Mazhar [3]
1. Professor of RC Structures, Faculty of Engineering, Ain Shams University.
2. Associate. Prof., Faculty of Engineering, Ain Shams University.
3. MSc student, Faculty of Engineering, Ain Shams University

الملخص العربي

في هذه الدراسة، تم تطوير برنامج حاسوبي "MATPRE.01 Software" من أجل التصميم الامثل للكمرات الخرسانية سابقة الإجهاد تحت الانحناء. يتم تحديد القيم المثلى لقوى الإجهاد، ابعاد القطاع الخرسانى و حديد التسليح وذلك وفقًا للقيود المفروضة على متغيرات التصميم. يوفر البرنامج الحاسوبي طريقة عملية وتفاعلية لتحسين تصميم الكمرات الخرسانيه سابقة الشد. يقوم البرنامج الحاسوبي تلقائيًا بإجراء تغييرات على متغيرات التصميم، وإجراء تحليل جديد لتقييم تأثير متغيرات التصميم على النتائج، وتكرار العملية حتى يحقق التصميم الأمثل.

Abstract

In this study, a computer program "MATPRE.01 Software" has been developed for design optimization of prestressed concrete beams under flexure. Optimum values of prestressing forces, eccentricities, cross sectional dimension and non-prestressed steel reinforcement are determined subject to constraints on the design variables. The developed computer program provides practical and interactive method for design optimization of simply supported pretension Standard AASHTO PC-I, NU I-Girders and California Bath Tub beams. MATPRE.01 Software automatically make changes to problem parameters that allowed to vary, referred to as design variables and perform a new analysis to evaluate the influence of changes, repeating the process until the best design satisfies performance and behavior requirements. The optimized results are then compared with ***PCI Bridge Design Manual 2011, 3rd Edition and Nebraska Department of Roads (NDOR).***

Keyword: *Optimization, MATPRE.01 Software, MATLAB, SAP2000 Application programming interface (API), SAP2000, Design Variables, Design Constraints, Objective function.*

1. Introduction

The optimum design procedure is an alternative to the traditional design approach transforming the conventional design process of trial and error to a formal systematic and digital computer based automated procedure that yields a design that is the best in the designer specified figure. In the present study, optimization of prestressed concrete beams is introduced, the optimization procedure is based on a design linear programming optimization code "MATPRE.01" has been developed using MATLAB software program and linked to the FEA software package "SAP2000" through the new SAP2000 Application programming interface (API) to evaluate the stresses and deflections during the optimization procedure. A study on the design optimization of prestressed concrete beams according to ***ACI 318-08***. The cost of prestressed concrete beams is influenced by several cost items including the cost of concrete, prestressing and non-prestressing reinforcement. In fact, the optimum cost design is a compromise between the consumption of concrete, prestressing and non-prestressing reinforcement which minimizes the total cost and satisfies the design requirements.

2. Problem Formulation

2.1 Constant Design Parameters

The constant design parameters under consideration are material properties of concrete and prestressing steel, superimposed dead loads and AASHTO live loads, strand size, deck slab thickness, girder spacing and number of lanes as shown below in tables (1).

Table (1): Constant Design Parameters

Parameter	Bridge Girder Sections								
	PC-I Type IV, NU 1600, NU 1800 & NU 2000				CA TUB61, CA TUB67 and CA TUB85				
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
f'_c (MPa)	55	40	55	40	55	40	55	40	55
f_{pu}(MPa)	1860								
f_{py}(MPa)	1670								
f_y(MPa)	460								
Strand diameter (mm)	15.2	15.2	12.7	12.7	15.2	15.2	12.7	12.7	15.2
t_s (mm)	200				200				
W_{SDL}(kN/m)	11.5				19.0				28.7
Live Load	HL93 Truck live load								
Girder Spacing (m)	1.82				3.0				4.5
Number of Lanes	One Lane								
C55/70 ($/m^3)	$115/m^3								
Prestressed Steel ($/tonnes)	$1640/tonnes								
NonPrestressed Steel ($/tonnes)	$820/tonnes								
Formwork ($/m^2)	$35/m^3								

The optimization was done considering the analysis of an interior girder of spacing of 1.82 m for Standard AASHTO PC-I Type V, NU 1600, NU 1800 and NU 2000 as shown below in fig. (1) and spacing of 3.0 m and 4.5 m for CA TUB61, CA TUB67 and CA TUB85 as shown below in fig. (2), the analysis are based on assuming that these members carry their own weight plus the topping weight of 200 mm thickness as non-composite, and 2.10 kN/m^2 superimposed dead load as composite members. The 2.10 kN/m^2 include allowance for barriers, railing and wearing surface as recommended by ***PCI Bridge Design Manual 2011, 3rd Edition***. HL93 truck loading is considered with single loaded lane considering a lane width of 3.65 m in accordance with ***AASHTO LRFD Bridge Construction Specifications, 4th Edition***, as shown below in fig. (3). The cost of the concrete, formwork, prestressed and non-prestressed reinforcement are considered based on United Arab of Emirates market price at year of (2018).

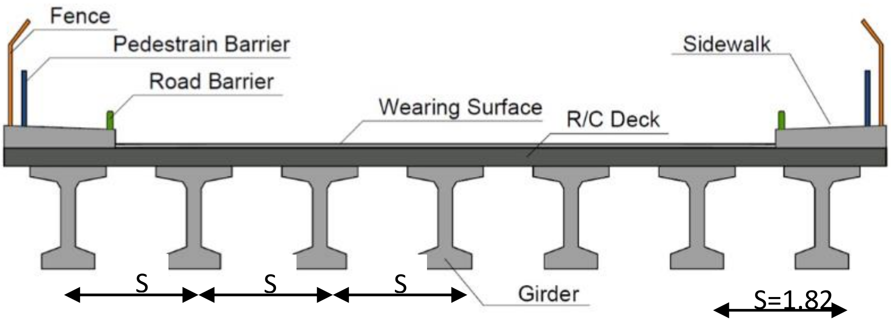


Fig. (1): Cross Section PC-I Type IV, or NU 1600, or NU 1800, or NU 2000 girder bridge

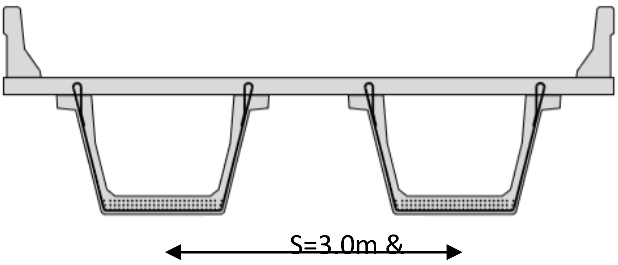


Fig. (2): Cross Section CA TUB61, or CA TUB67, or CA TUB85 girder bridge

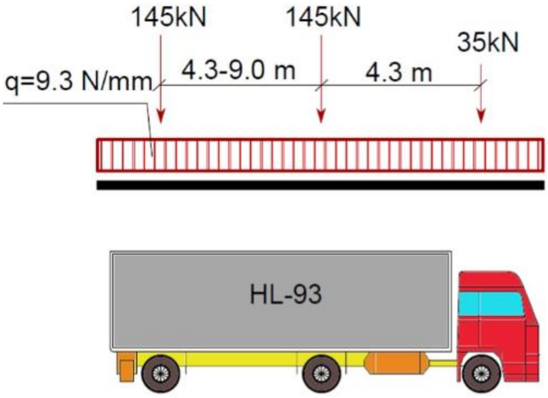


Fig. (3): HL93 Truck Live Load as per AASHTO LRFD Bridge Construction Specifications, 4th Edition

2.2 Design Variables

The design variables under consideration are the cross-section dimension of Standard AASHTO PC-I Type IV, NU 1600, NU 1800, NU 2000, CA TUB61, CA TUB67 and CA TUB85 as shown below in fig. (4), number of strands, eccentricity to c.g of prestressed concrete beam, number and diameter of non-prestressed reinforcement.

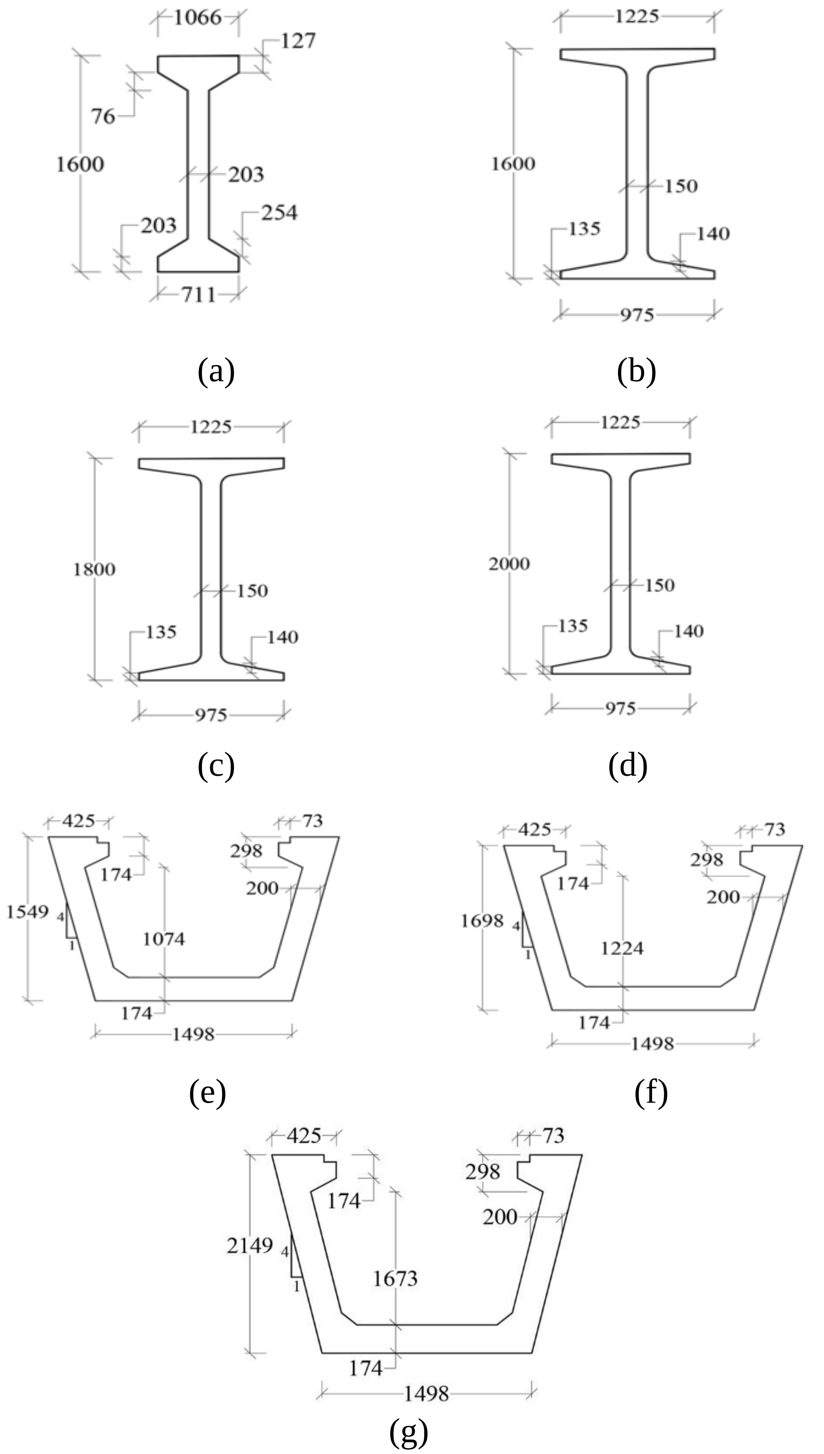


Fig. (4): Cross-Section Dimension Design Variables, (a) Standard AASHTO PC-I Type V, (b) NU 1600, (c) NU 1800, (d) NU 2000, (e) CA TUB61, (f) CA TUB67 and (g) CA TUB85

2.3 Design Constraints

These constraints describe the behavior and performance requirements of bridge system.

2.3.1 Flexure Working Stress Constraint

The allowable tension stresses are $0.5\sqrt{f'_c}$ at service and $0.25\sqrt{f'_{ci}}$ at release, the allowable compressive stresses are $0.6\,f'_c$ at service and $0.6\,f'_{ci}$ at release as per the recommended values by ***PCI Bridge Design Manual 2011, 3rd Edition***. The allowable tension stresses are checked against 100% of the total dead loads in addition to 80% of the live load plus impact as per ***AASHTO LRFD Bridge Construction Specifications, 4th Edition***. The actual stress are calculated as shown below:

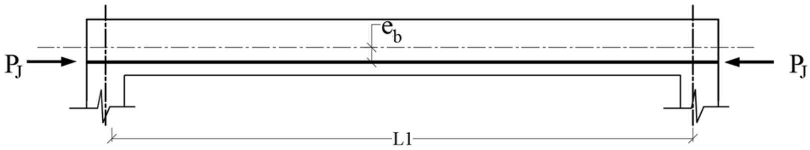


Fig. (5): Simply Supported Pretension Girder under Study

$$f_{bt} = \left(\frac{-P_i}{A_c} \mp \frac{M_{P_i} \times y_b}{I} \pm \frac{M_{sw} \times y_b}{I}\right) \quad (1)$$

$$f_{tt} = \left(\frac{-P_i}{A_c} \pm \frac{M_{P_i} \times y_t}{I} \mp \frac{M_{sw} \times y_t}{I}\right) \quad (2)$$

$$f_{be} = \left(\frac{-P_e}{A_c} \mp \frac{M_{P_e} \times y_b}{I} \pm \frac{M_{tot} \times y_b}{I}\right) \quad (3)$$

$$f_{te} = \left(\frac{-P_e}{A_c} \pm \frac{M_{P_e} \times y_t}{I} \mp \frac{M_{tot} \times y_t}{I}\right) \quad (4)$$

f_{bt} and f_{tt} are the actual stresses at bottom and top fibers of prestressed concrete beam at transfer stage respectively, f_{be} and f_{te} are the actual stresses at bottom and top fibers of prestressed concrete beam at service stage respectively. P_i and P_e are the prestressing forces after short and long-term losses respectively, M_{P_i} and M_{P_e} are the moments due to prestressing forces after short and long-term losses respectively.

2.3.2 Ultimate Flexural Strength Constraint

MATPRE.01 Software calculates the nominal moment strength (ϕM_n) by the analysis based on stress and strain computability as singly reinforced section using the stress-strain properties of prestressing steel and assumption as per ***ACI 318-08 clause 10.2*** by considering the strain at which ultimate moments are developed is about 0.003, the nominal moment strength of rectangular and flanged section is calculated as shown below in equations (5) and (6) respectively.

$$\phi M_n = \phi(A_{ps}\, f_{ps}\, (d_{ps} - a/2) + A_s\, f_y\, (d_s - a/2)) \quad (5)$$

$$\phi M_n = \phi(A_{pw}\, f_{ps}\, (d_{ps} - a/2) + A_s\, f_y\, (d_s - d_{ps}) + 0.85 f'_c\, (b_f - b_w)\, t_f\, (d_{ps} - t_f/2)) \quad (6)$$

d_s , is the effective depth of non-prestressing reinforcement to compression fiber, a is the depth of equivalent stress block are calculated as shown below in equation (7), in case the equivalent stress block depth (a) is within the flange depth $\left(a < t_f\right)$, the section should will be considered as rectangular section. A_{pw} is the prestressing reinforcement corresponding to part of the total tension force developed to balance the web, the term $\left(0.85 f_c' \left(b_f - b_w\right) t_f \left(d_{ps} - t_f/2\right)\right)$ in equation (6) is part of the total tension force developed to balance the flange and ϕ is the strength reduction factor to be taken as 0.9 for tension controlled section as per ***ACI 318-08 clause 9.3.2.1.***

$$a = \frac{A_{ps}\ f_{ps}\ + A_s f_y}{0.85 f_c' B_c} \qquad (7)$$

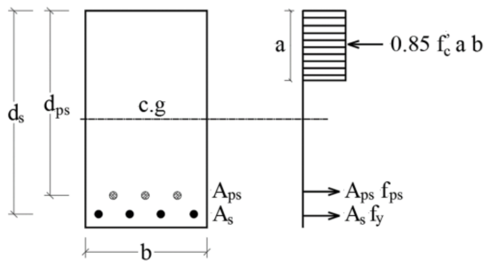


Fig. (6): Stresses and Forces Across Singly Reinforced Rectangular Section

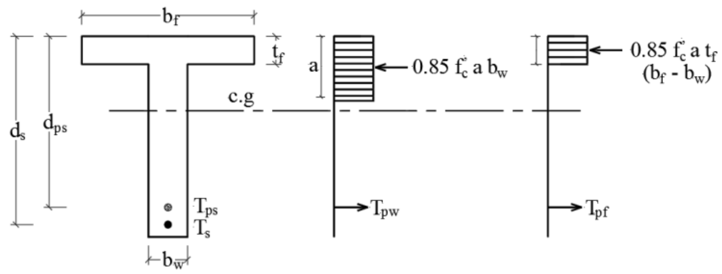


Fig. (7): Stresses and Forces Across Singly Reinforced Flanged Section

2.3.3 Ultimate Shear Strength Constraint

MATPRE.01 Software formulated the nominal shear strength (ϕV_n) as per ***ACI 318-08 clause 11.1***, the nominal shear strength is calculated as shown below in equation (8).

$$\phi V_n = \phi (V_c + V_s) \qquad (8)$$

V_c, is the shear strength provided by concrete which is permitted to be the lesser of the nominal shear strength provided by concrete when diagonal cracking results from both shear and moment (V_{ci}) and the nominal shear strength provided by concrete when diagonal cracking results from principle tensile stress through the web (V_{cw}) as per ***ACI 318-08 clause 11.4.3.*** (V_{ci}) and (V_{cw}) can be calculated as shown below in equations (9) and (10) respectively, V_s is the shear strength force provided by stirrups where the ultimate shear force is exceeding shear strength force provided by concrete (V_c) and ϕ is the strength reduction factor to be taken as 0.75 as per ***ACI 318-08 clause 9.3.2.3***.

$$V_{ci} = 0.05\sqrt{f_c'} b_w d_{ps} + V_d + \frac{V_i M_{cre}}{M_{max}} \geq 0.14\sqrt{f_c'} b_w d_{ps} \qquad (9)$$

$$V_{cw} = \left(0.29\sqrt{f_c'} + 0.3f_{cp}\right)b_w\, d_{ps} \tag{10}$$

b_w, is the prestressed concrete beam web thickness, d_{ps} is the distance from the extreme compression fiber to centroid of prestressed and non-prestressed reinforcement not greater than 80 % of the total depth, V_d is the shear force due to unfactored dead load, V_i is the factored shear force due to external applied loads occurring simultaneously with maximum moment, M_{cre} is the moment causing flexure cracking due to external applied loads can be calculated as shown below in equation (11) and f_{cp} is the stress due to effective prestressing force at c.g of prestressed concrete beam cross section and can be computed as $\left(f_{cp} = \frac{P_e}{A_c}\right)$.

$$M_{cre} = \left(\frac{I}{y}\right)\left(0.5\sqrt{f_c'} + f_{pe} - f_d\right) \tag{11}$$

f_{pe}, is the compressive strength in concrete due to effective prestress after long term losses and f_d is the stress due to unfactored dead load at the extreme fiber where tensile stresses are caused by external loads. The lower and upper bound of the shear strength provided by concrete (V_c) can be as shown below.

$$0.17\sqrt{f_c'}b_w d \le V_c \le 0.42\sqrt{f_c'}b_w d \tag{12}$$

2.3.4 Deflection Constraint

MATPRE.01 Software formulates the deflection constraints as shown below in equations (13).

$$\Delta_L \le \frac{L}{240} \tag{13}$$

Δ_L, is the long-term deflection can be calculated for composite sections as shown below in equations (14).

$$\Delta_L = \left(\left(2.20 \times \Delta_{P_e}\right) + \left(2.40 \times \Delta_{sw_{(elastic)}}\right) + \left(3.0 \times \Delta_{SDL_{(elastic)}}\right) + \left(1.30 \times \Delta_{LL_{(elastic)}}\right)\right) \tag{14}$$

Δ_{P_e}, $\Delta_{sw_{(elastic)}}$, $\Delta_{SDL_{(elastic)}}$ and $\Delta_{LL_{(elastic)}}$ are the elastic deflection due to effective prestressing forces, self-weight, superimposed dead loads and live loads respectively.

2.3.4 Objective Function

In this study, the objective function is to determine the minimum number of pretension strands that bridge girder require to comply with the allowable tension and compression stresses at transfer and service stage, ultimate flexure strength, ultimate shear strength and deflection requirements.

3. Optimization Procedure

MATPRE.01 Software using linear programming optimization technique for design optimization of prestressed concrete beams considering the new SAP2000 Application programming interface (API) in order to develop a new computational tool that implements the evaluation of behavior, performance and response of the prestressed concrete beams. This API was recently introduced by CSI, the developer of the finite element code SAP2000, and grant access to SAP2000 advanced numerical modules, thus permitting pre-analysis and post-analysis computations to be efficiently programmed, the API is a programming tool which aims to offer efficient access to the analysis and design technology of SAP2000 structural analysis software, by allowing during run time, a direct bind to be established between the third party application (MATPRE.01) and the analysis software itself as shown below in fig. (8).

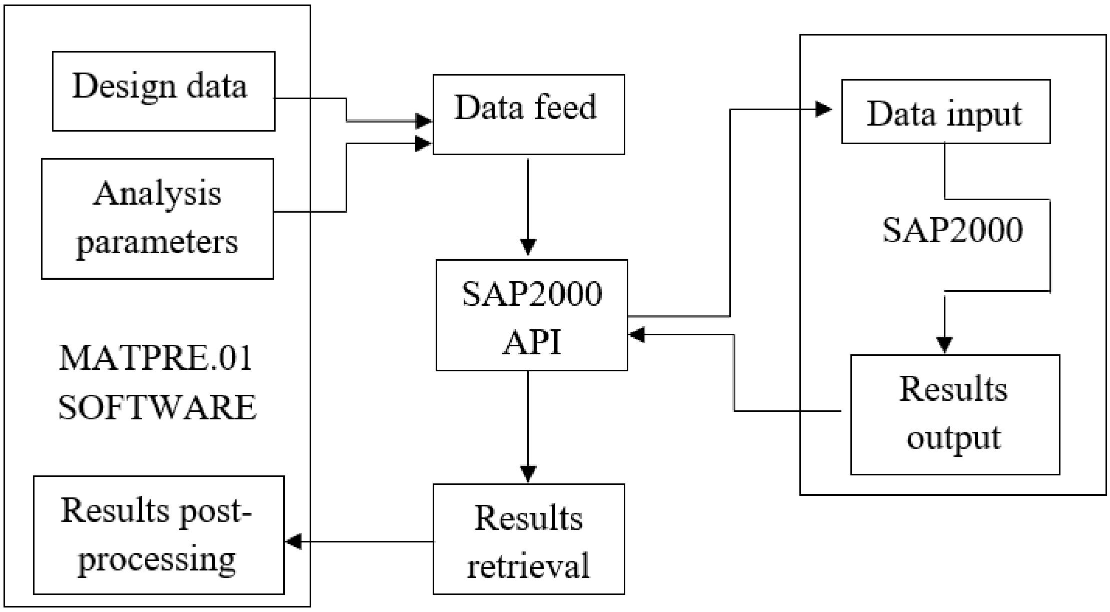


Fig. (8): Application binding and typical data flow using SAP2000 API

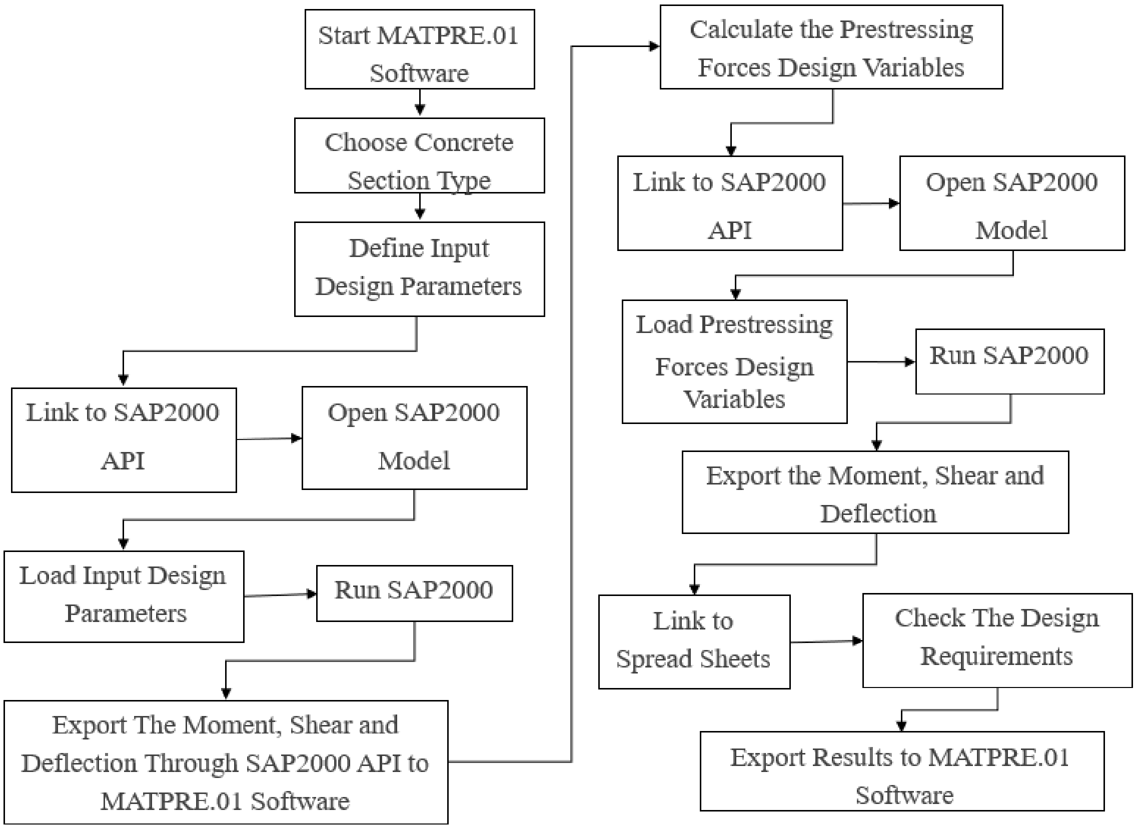


Fig. (9): MATPRE.01 Software Optimization Procedure Chart

MATPRE.01 Software consider ten prestressing jacking forces for each prestressed concrete beam cross-section through the optimization process, the prestressing jacking forces are calculated in accordance with the linear programming formulas considering maximum eccentricities of pretension strands and the flexure working stress constraints as shown below in equation (15).

$$\begin{aligned} &\text{Minimize} && Z = P_j \\ &\text{Subjected to,} && f_{ci} \leq f_{bt} \leq f_{ti} \\ &&& f_{ci} \leq f_{tt} \leq f_{ti} \\ &&& f_{cw} \leq f_{be} \leq f_{tw} \\ &&& f_{cw} \leq f_{te} \leq f_{tw} \end{aligned} \quad (15)$$

In order to determine the prestressing forces design variables, new design variables of $(X_A, X_B, X_C, X_F, X_G, X_T, X_Y \& X_Z)$ are entering the optimization process as shown below.

$$X_A = \frac{1}{A_c} \quad (16)$$

$$X_B = \frac{y_b}{I} \quad (17)$$

$$X_C = \frac{y_t}{I} \quad (18)$$

$$X_D = P_j \tag{19}$$
$$X_E = M_p \tag{20}$$
$$X_F = (M_{sw} \times X_B) \tag{21}$$
$$X_G = (M_{sw} \times X_C) \tag{22}$$
$$X_T = (M_{tot} \times X_B) \tag{23}$$
$$X_Y = (M_{tot} \times X_C) \tag{24}$$

The linear programming formulas in the developed optimization model used to generate the prestressing forces design variables are as shown below in equation (25).

$$\begin{gathered} F = [1; 0]; \\ \text{Subjected to,} \quad [AX] \leq [B] \\ A_{eq} = [] \\ B_{eq} = [] \\ L = [0; 0;]; \\ u = []; \\ P_j = x = \text{linprog}\left(F, A, B, A_{eq}, B_{eq}, l, u\right) \\ n_{s_{(1,2,\ldots,10)}} = \frac{(0.92, 0.925, \ldots\ldots, 1.10) \times P_j}{\text{force}_{(\text{strand})}} \end{gathered} \tag{25}$$

(F), is the objective function to be minimized, matrix $(A\,X)$ are the actual stresses due to prestressing at transfer and service stage, matrix (B) are the allowable tension and compression stresses at transfer and service stage in addition to stresses due to the applied loads, matrix $[A_{eq}]$ and matrix $[B_{eq}]$ contain null values as the optimization problem is based on inequality constraints only, matrix $[L]$ is zero means the lower limit of the design variables are zero, and matrix $(u = [];)$ means the upper limit of the design variables are infinity. Matrices $[AX]$ and $[B]$ of simply supported pretension girder as shown below in table (2).

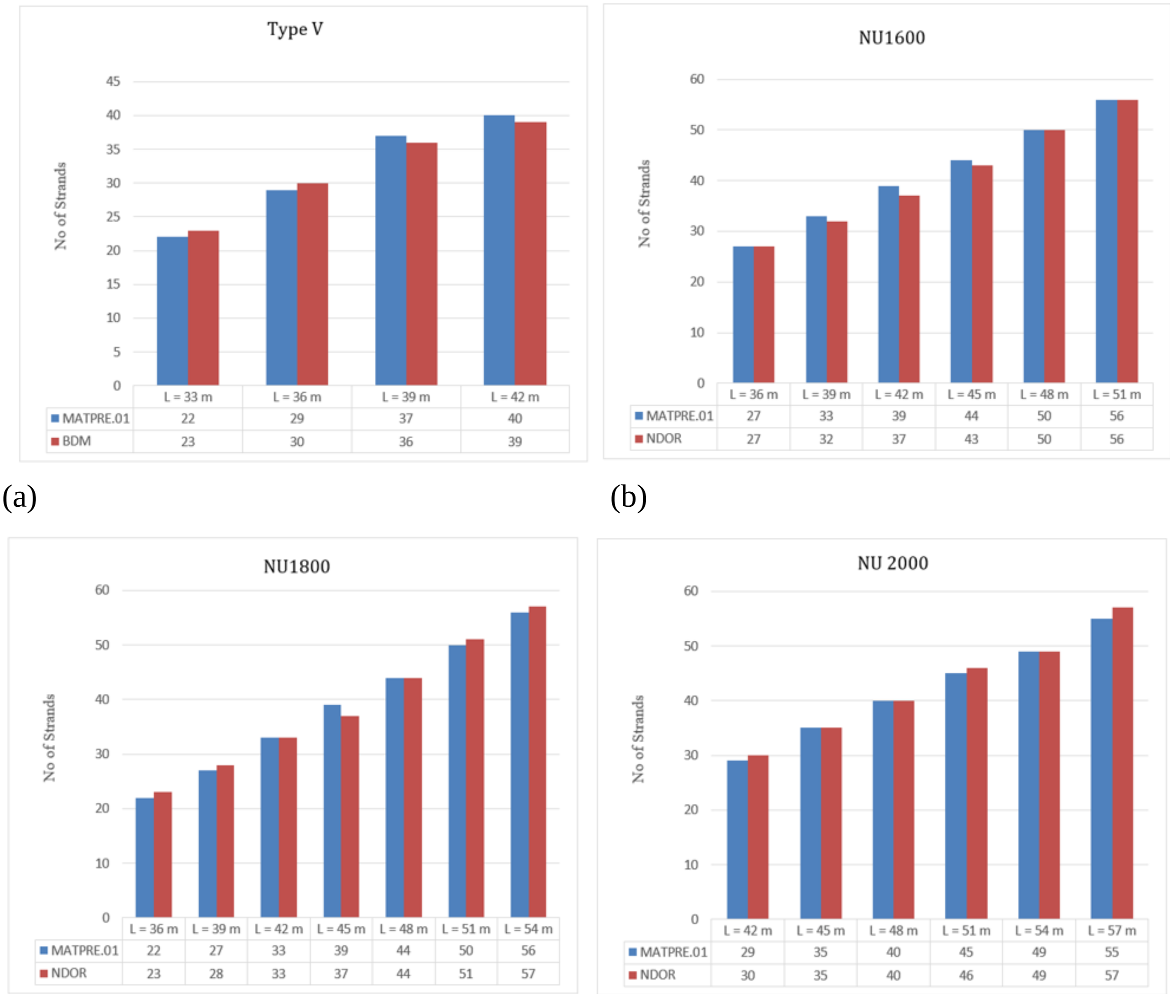
Table (2): $(A\,X)$ and (B) matrices of simply supported pretension girder

[AX]	[B]
$\begin{bmatrix} -C_2X_AX_D & -C_2X_BX_E \\ C_2X_AX_D & C_2X_BX_E \\ -C_2X_AX_D & C_2X_CX_E \\ C_2X_AX_D & -C_2X_CX_E \\ -C_3X_AX_D & -C_3X_BX_E \\ C_3X_AX_D & C_3X_BX_E \\ -C_3X_AX_D & C_3X_CX_E \\ C_3X_AX_D & -C_3X_CX_E \\ -X_DX_E & 1 \end{bmatrix}$	$\begin{bmatrix} f_{ti} - X_F \\ f_{ci} + X_F \\ f_{ti} + X_G \\ f_{ci} - X_G \\ f_{tw} - X_T \\ f_{cw} + X_T \\ f_{tw} + X_Y \\ f_{cw} - X_Y \\ 0 \end{bmatrix}$

C_2 and C_3 are the multipliers coefficient to account for short and term-losses respectively equal to 0.9 and 0.7 respectively.

4. Verification of The Optimization Model

Verification is done by comparing the output results of the required number of pretension strands of Standard AASHTO PC-I Type V, NU 1600, NU 1800 & NU 2000 from MATPRE.01 Software and the recommendation of ***PCI Bridge Design Manual 2011, 3rd Edition and Nebraska Department of Roads (NDOR)*** considering concrete compressive strength (f_c') of 55 MPa and strand diameter of 15.2 mm as shown below in fig. (10).



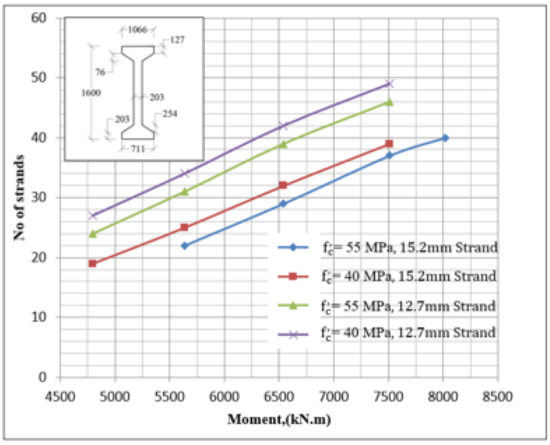
(a) (b)

(c) (d)

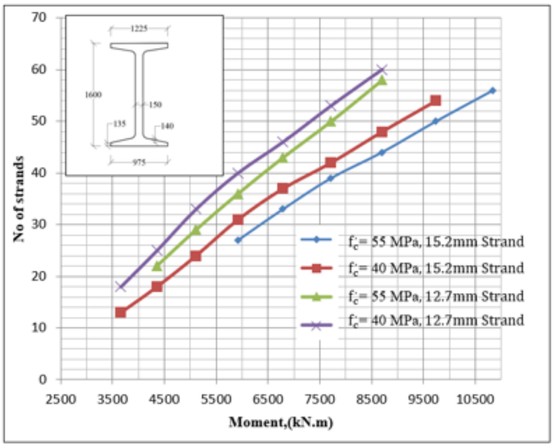
Fig. (10): Verification of MATPRE.01 Software

5. Parametric Study

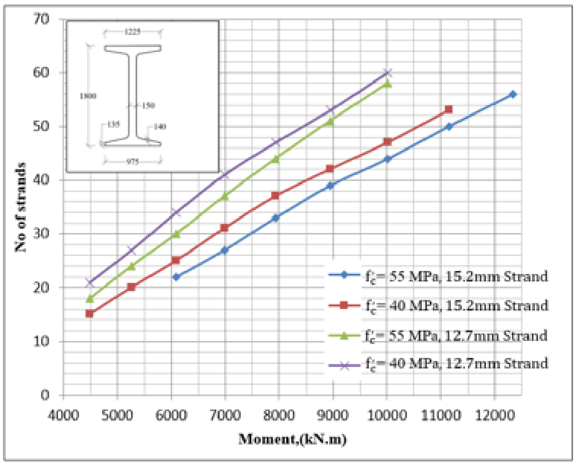
The required minimum number of pretension strands developed by MATPRE.01 Software versus the service moment for Standard AASHTO PC-I Type IV, NU 1600, NU 1800, NU 2000, CA TUB61, CA TUB67 and CA TUB85 for girder span of (30, 33, 36, 39, 42, 45, 48, 51, 54 & 57) with respect to constant design parameters of concrete cylinder compressive strength, ultimate and yielding tensile strength of prestressing steel, strand diameter, girder spacing, superimposed dead loads and live loads cases (1,2 ,3, 4, 5, 6, 7 & 8) illustrated in table (1) are as shown below in fig. (11).



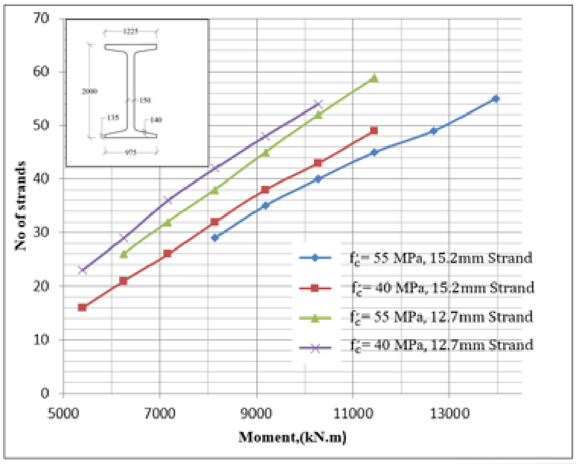
(a)



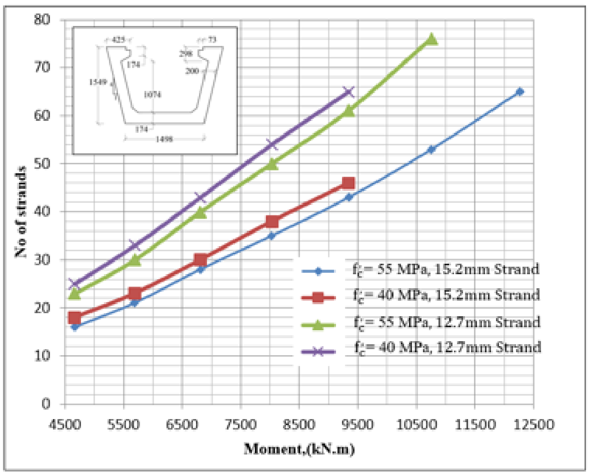
(b)



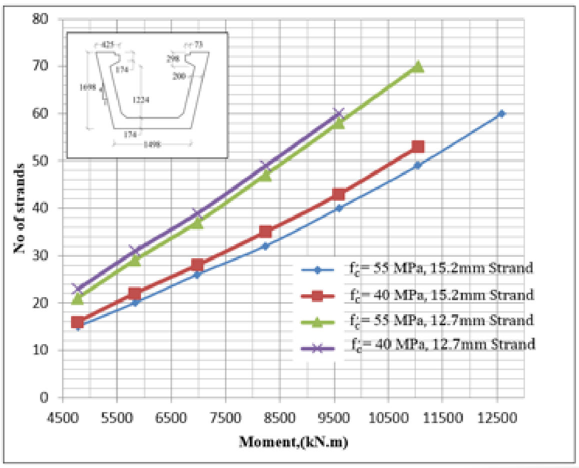
(c)



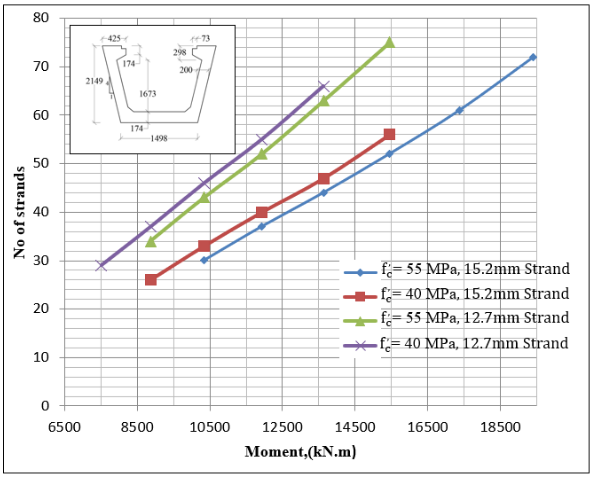
(d)



(e)



(f)



(g)

Fig. (11): Required number of pretension strands developed by MATPRE.01 Software, (a) Standard AASHTO PC-I Type V, (b) NU 1600, (c) NU 1800, (d) NU 2000, (e) CA TUB61, (f) CA TUB67 and (g) CA TUB85

Cost analysis was performed considering constant design parameters illustrated in table (1) of cases (1, 5 & 9). The total cost per square meter includes the cost of the concrete, formwork, prestressed and non-prestressed reinforcement. The cost function can be written as shown below in equation (26).

$$C_T = UP_c V + UP_f A_f + UP_{ps} W_{ps} + UP_s W_s \qquad (26)$$

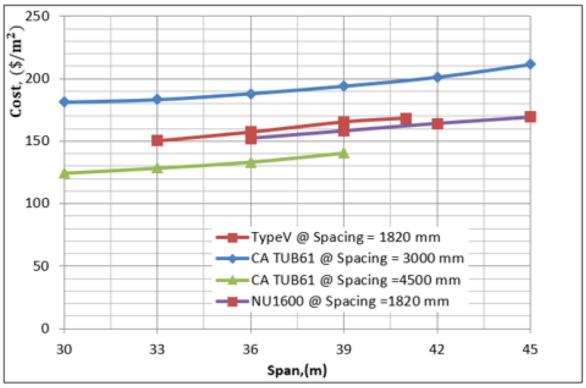
C_T, is the total cost of the prestressed concrete girder bridge per square meter, UP_c, UP_f, UP_{ps} and UP_s are the unit prices concrete, formwork, prestressed and non-prestressed reinforcement respectively, V is the quantity of concrete in m^3, A_f is the area of the formwork in m^2, W_{ps} and W_s are the quantities of prestressed and non-prestressed reinforcement respectively. Comparison between the cost prices per square meter of Standard AASHTO PC-I Type V, NU I-Girders (NU-1600, NU-1800 & NU-2000) considering girder spacing of 1.8 m are as shown in table (3) and CA TUB61, CA TUB67 and CA TUB85 considering girder spacing of (3.0 & 4.5) m are as shown in tables (4).

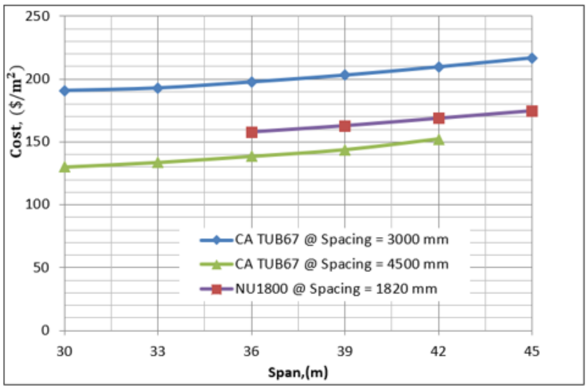
Table (3): Cost comparison between Standard AASHTO PC-I Type V and NU I-Girders (NU-1600, NU-1800 & NU-2000)

Type	L	V	A_f	W_{ps}	W_s	UP_cV	UP_fA_f	$UP_{ps}W_{ps}$	UP_sW_s	C_T
V	33.0	20.96	130.35	0.80	0.76	2409.83	4562.38	1308.51	660.23	148.87
	36.0	22.86	142.09	1.15	0.82	2628.90	4973.10	1881.66	714.71	155.65
	39.0	24.77	153.82	1.59	0.89	2847.98	5383.82	2600.81	776.81	163.56
NU1600	36.0	18.97	151.36	1.07	0.73	2181.78	5297.46	1751.89	633.47	150.56
	39.0	20.55	163.88	1.41	0.79	2363.60	5735.83	2319.64	688.71	156.49
	42.0	22.13	176.41	1.80	0.85	2545.41	6174.21	2952.27	741.50	162.39
	45.0	23.72	188.93	2.18	0.92	2727.23	6612.58	3568.67	796.74	167.34
	48.0	25.30	201.46	2.64	0.97	2909.04	7050.96	4325.66	844.62	173.19
	51.0	26.88	213.98	3.14	1.03	3090.86	7489.33	5147.54	899.86	179.14
NU1800	36.0	19.80	165.82	0.87	0.82	2277.00	5803.56	1427.47	709.91	155.95
	39.0	21.45	179.54	1.16	0.89	2466.75	6283.93	1897.89	771.84	160.90
	42.0	23.10	193.27	1.52	0.96	2656.50	6764.31	2498.07	831.00	166.80
	45.0	24.75	206.99	1.93	1.03	2846.25	7244.68	3163.14	892.92	172.73
	48.0	26.40	220.72	2.32	1.09	3036.00	7725.06	3806.58	946.55	178.30
	51.0	28.05	234.44	2.80	1.16	3225.75	8205.43	4596.02	1008.47	183.53
	54.0	29.70	248.17	3.32	1.23	3415.50	8685.81	5450.34	1067.63	189.45
NU2000	45.0	26.46	225.05	1.43	1.14	3042.90	7876.78	2352.08	988.79	174.12
	48.0	28.22	239.98	1.85	1.20	3245.76	8399.16	3027.96	1048.15	179.96
	51.0	29.99	254.90	2.24	1.28	3448.62	8921.53	3676.81	1116.73	184.91
	54.0	31.75	269.83	2.67	1.36	3651.48	9443.91	4379.73	1182.24	189.84
	57.0	33.52	284.75	3.07	1.44	3854.34	9966.28	5033.99	1250.82	195.30
	60.0	35.28	299.68	3.63	1.51	4057.20	10488.66	5947.79	1310.19	199.67

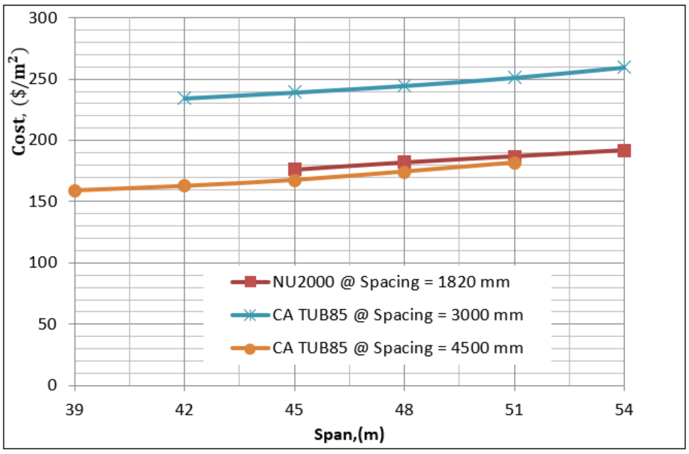
Table (4): Cost comparison between CA TUB61, CA TUB67 and CA TUB85

Type	L	V	A_f	W_{ps}	W_s	UP_cV	UP_fA_f	$UP_{ps}W_{ps}$	UP_sW_s	C_T
CA TUB61 @ 3.0 m	30.0	27.77	269.84	0.92	2.48	3194.01	9444.51	1513.98	2155.03	181.19
	33.0	30.55	296.83	1.27	2.47	3513.41	10388.97	2081.73	2153.18	183.20
	36.0	33.33	323.81	1.70	2.70	3832.81	11333.42	2790.05	2348.92	188.01
	39.0	36.11	350.80	2.27	2.92	4152.21	12277.87	3725.48	2544.66	194.02
	42.0	38.88	377.78	3.00	3.15	4471.61	13222.32	4920.44	2740.41	201.23
	45.0	41.66	404.76	4.06	3.37	4791.02	14166.77	6650.71	2936.15	211.44
CA TUB67 @ 3.0 m	30.0	29.63	287.75	0.86	2.63	3407.57	10071.26	1405.84	2288.31	190.81
	33.0	32.59	316.53	1.16	2.71	3748.32	11078.38	1903.29	2358.80	192.82
	36.0	35.56	345.30	1.58	2.96	4089.08	12085.51	2595.40	2573.24	197.62
	39.0	38.52	374.08	2.10	3.20	4429.83	13092.64	3444.31	2787.67	203.03
	42.0	41.48	402.85	2.77	3.45	4770.59	14099.76	4541.95	3002.11	209.64
	45.0	44.45	431.63	3.56	3.70	5111.35	15106.89	5839.65	3216.55	216.85
CA TUB85 @ 3.0 m	39.0	45.77	444.41	1.59	4.05	5263.15	15554.28	2600.81	3527.61	230.31
	42.0	49.29	478.59	2.03	4.37	5668.01	16750.76	3330.76	3798.96	234.51
	45.0	52.81	512.78	2.57	4.68	6072.86	17947.24	4217.52	4070.32	239.32
	48.0	56.33	546.96	3.22	4.99	6477.72	19143.73	5277.31	4341.67	244.73
	51.0	59.85	581.15	4.04	5.30	6882.58	20340.21	6618.27	4613.03	251.33
	54.0	63.37	615.33	5.10	5.61	7287.44	21536.69	8370.16	4884.38	259.74
CA TUB61 @ 4.5 m	30.0	27.77	269.84	1.35	2.25	3194.01	9444.51	2216.90	1957.43	124.54
	33.0	30.55	296.83	1.85	2.47	3513.41	10388.97	3033.37	2153.18	128.54
	36.0	33.33	323.81	2.49	2.70	3832.81	11333.42	4087.75	2348.92	133.35
	39.0	36.11	350.80	3.47	2.92	4152.21	12277.87	5693.66	2544.66	140.56
CA TUB67 @ 4.5 m	30.0	29.63	287.75	1.19	2.46	3407.57	10071.26	1946.55	2144.36	130.15
	33.0	32.59	316.53	1.63	2.71	3748.32	11078.38	2676.50	2358.80	133.75
	36.0	35.56	345.30	2.26	2.96	4089.08	12085.51	3698.44	2573.24	138.56
	39.0	38.52	374.08	3.00	3.20	4429.83	13092.64	4920.44	2787.67	143.76
	42.0	41.48	402.85	4.20	3.45	4770.59	14099.76	6888.62	3002.11	152.18
CA TUB85 @ 4.5 m	39.0	45.77	444.41	2.19	4.05	5263.15	15554.28	3584.89	3527.61	159.14
	42.0	49.29	478.59	2.77	4.37	5668.01	16750.76	4541.95	3798.96	162.75
	45.0	52.81	512.78	3.56	4.68	6072.86	17947.24	5839.65	4070.32	167.56
	48.0	56.33	546.96	4.69	4.99	6477.72	19143.73	7699.68	4341.67	174.36
	51.0	59.85	581.15	6.00	5.30	6882.58	20340.21	9835.48	4613.03	181.57





(a) (b)



(c)

Fig. (12): Cost Analysis Comparison ($\$/m^2$) of Standard AASHTO PC-I Type V, NU I-Girders (NU-1600, NU-1800 & NU-2000), CA TUB61, CA TUB67 and CA TUB85

6. Conclusion

A digital computer program is developed that may be useful to designers and contractors interested in design optimization of prestressed concrete beams. The influence of constant design parameters, such as unit cost of materials, concrete strength, girder spacing and concrete section type on the optimum design is studied. Higher concrete cylinder compressive strength of 55 MPa comparing with concrete cylinder compressive strength of 40 MPa increasing the allowable tension stresses at service stage by 17 % leads to reduction in required number of strands of (8 to 10) %. Larger strand diameter of 15.2 mm about 20 % more than 12.7 mm strand provide 40 % higher tensile capacity of pretension strands leads to reduction in required number of strands of (25 to 30) %. California Bath TUB sections at spacing of 4500 mm comparing with spacing of 3000 mm leads to increasing the required number of strands of (35 to 45) % per girder and reduction of the total cost per square meter of 30 %. CA TUB61 at spacing of 4500 mm comparing with Standard AASHTO PC-I Type V and NU I-Girder 1600 at spacing of 1820 mm leads to reduction in the total cost per square meter of 15 % and 22 % respectively. CA TUB67 at spacing of 4500 mm comparing with NU I-Girder 1800 at spacing of 1820 mm leads to reduction in the total cost per square meter of 12 %. CA

TUB85 at spacing of 4500 mm comparing with NU I-Girder 2000 at spacing of 1820 mm leads to reduction in the total cost per square meter of 5 %.

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