Sakarya University Journal of Science 24(4), 575-585, 2020

A Case Study on Two-Span Post-Tensioned Concrete Bridge Decks with Different Span Lengths and Investigation on Prestressing Tendons with Comparisons

Mustafa TURAN*1

Abstract

Post-Tensioned (PT) concrete system is one of the widely used bridge superstructure types because of its better load capacity performance. By increasing load carrying capacities on conventional reinforced concrete structures, PT is considered as an advanced technology in engineering. The aim of this paper is to study on finite element analysis of two-span PT concrete bridge decks with different span lengths. For three different span lengths, two-span bridge decks were investigated. To reduce the self-weight of the deck, at mid spans, deck section was used as voided section and at diaphragm regions, section was used as filled. Two-dimensional Finite Element (FE) deck models were created by frame elements. The FE software package Midas Civil was used. Permanent, transient and time-dependent loading types were considered. Boundary conditions were defined with their real mechanical properties. To balance the deck section stresses, prestressing tendons were used. By iterations, PT tendons layout and types were studied. Interaction between span lengths and PT tendons areas was investigated. Also, different effects on PT tendons were studied and relevant comparisons were submitted. The "best" tendon using was examined for the investigated deck sections. Concluded that optimization on PT tendon areas at bridge deck sections is possible by investigating the main effects on it. Results show that a good optimization enables us to have the optimal PT tendon using with lower cost.

Keywords: bridge, deck, post-tensioned, tendon-optimization

* Corresponding Author: mustafa.turan.ce@gmail.com
[1] Gazi University, Ankara, Turkey, ORCID: https://orcid.org/0000-0002-4601-8041

1. INTRODUCTION

Concrete and steel materials are the two main materials used in most structure types. Using two elements in a good harmony creates a strong element which has a real load carrying capacity. In some cases, aforementioned element capacity needs to be support by external effects. Prestressing is a good way and an advanced technology on reinforced concrete elements. Application of prestressing gives section a compression stress which can be handled by concrete. In other words, prestressing aims to use high compressive strength of concrete material and reduce the tension stress on concrete section. This technology is broadly used for especially long spans like bridges, residential buildings, hotels, architectural structures.

Prestressing has two main application methods which are pre-tensioning and post tensioning. As the names imply, in pre-tensioning, tendons are stressed before concrete pouring. In post tensioning system, tendons are stressed after concrete gets initial pouring. In this paper, post-tensioning (PT) technology on bridge deck was investigated.

The use PT system allows passing long spans with more reasonable sections. This brings material savings due to reduced superstructure thickness compared to conventional slab types. By reducing deck thickness, bridge aesthetics can be emphasized. Also, reducing elements geometric properties leads to cost effectiveness which is the “greatest” point mostly in designs. There are many design variables in PT system. Hence, by designer, optimum design conditions should be investigated thoroughly.

PT concrete idea was developed in 1928 by Eugene Freyssinet and one year later, in 1929, an application was done. Since then, the idea and applications developments are still in progress.

Many articles and researches have been published addressing the behavior of PT concrete structural members [1-4]. In most studies, to understand real behavior, nonlinear models have been created. By defining time dependent parameters, not only primary but also secondary effects have been investigated.

About tendon optimization issues, many researchers have studied on different scenarios and investigated different effects on tendon usage [5-10]. Optimization technique plays a significant role in structure design. There are huge numbers of parameters that affect the design. The aim is to reach the “best” one. In mentioned structure type, optimal design refers to reach the maximum performance in different loading cases, minimum weight with reasonable concrete sections, minimum steel areas usage and minimum cost or a good combination of these.

In this paper, tendon using and optimization was investigated from different angles because one of the most important parts in design PT is deciding tendon types, tendon layout and tendon mechanical properties. Two-span bridge decks which have three different span lengths were created by FE model. All three bridges have equal geometric and mechanical properties except from span lengths. To reduce self-weight of the deck, voided sections were used at mid-spans and filled sections were used at supports. Frame elements were used for two-dimensional FE deck model. At each end, two elastomeric supports were designed. Mechanical properties of elastomeric bearings were calculated and assigned. All types of loads which are permanent, transient and time-dependent were considered. For the deck stresses at top and bottom of the section, tendons were placed in an engineering manner. At mid-spans, tendons were placed near the bottom face. At supports; tendons were placed at top face to balance tension stresses. For the same deck typical sections, tendons were compared in bridges having different span lengths and comparison results were evaluated.

2. MODELING STRATEGIES

2.1. Deck Geometries

In the scope of the study, 3 types of deck analysis models were investigated. Whole typical section properties were equal in each type but span lengths were different.

Type 1: 2 x 32.00 m.

Type 2: 2 x 34.00 m.

Type 3: 2 x 36.00 m.

Deck section is cast in situ, post-tensioned concrete voided and filled section. Deck width is 10.00 m and its depth is 1.20 m. To reduce self-weight of the deck, 6 recesses are planned in the section each has 0.70 m diameter. Flange and web thicknesses are 25 cm and 30 cm, respectively.

At pier and abutment axis region, a filled section is planned to resist shear forces by huge concrete section area. At typical section, 2 x 1.50 m width side walking is planned and at middle, 7.00 m asphalt width serves for 2 lanes. Thickness of the asphalt layer is 6.00 cm.

2.2. Design Codes

The design calculations are based on “AASHTO LRFD Bridge Design Specifications 2007 SI”.

2.3. Engineering Software

Midas Civil, 2019 (v2.1) was used as FE engineering software.

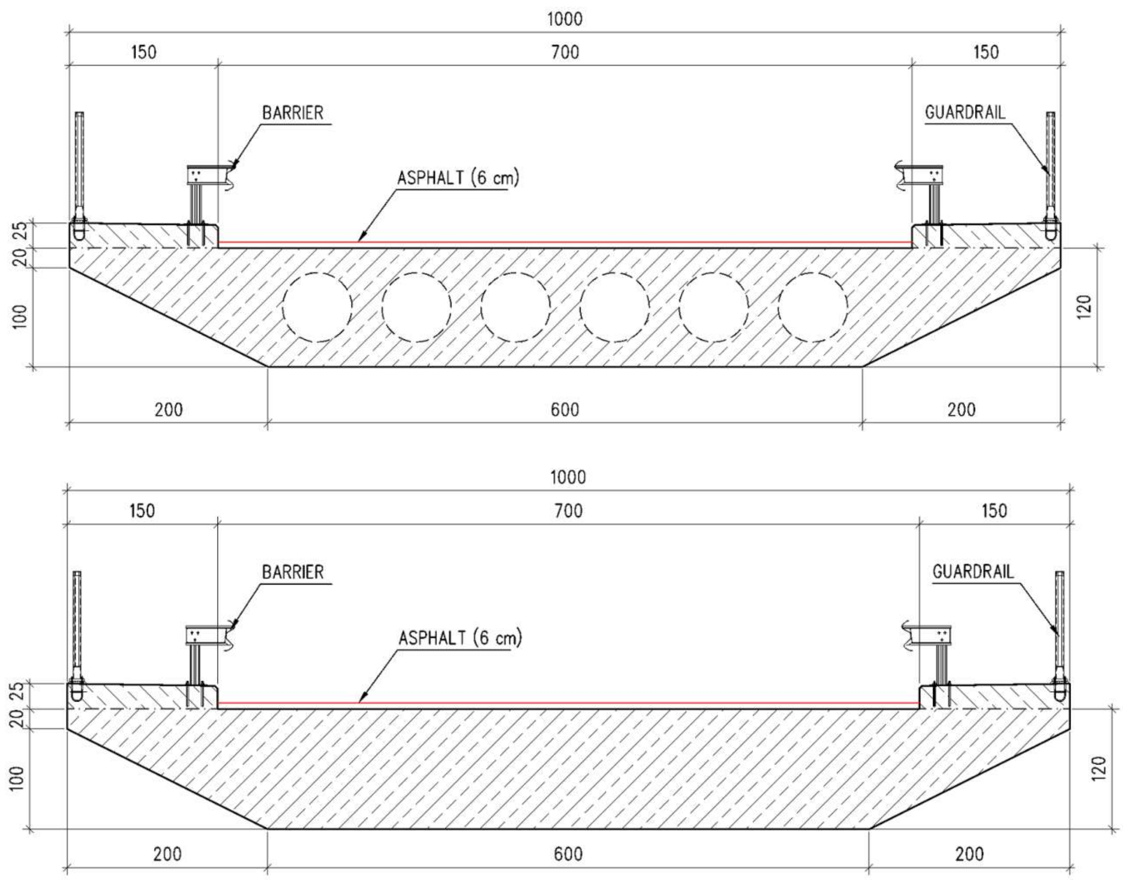

Figure 1. Voided and Filled Deck Typical Sections

2.4. Materials

Table 1. Concrete Properties

Class	Compressive Strength, f_{cy}	Modulus of Elasticity, E_c
-	(MPa)	(MPa)
C35/45	34000	25

Unit Weight	Poisson Ratio	Thermal Expansion Coefficient
(kN/m^3)	-	(1/^{o}C)
25	0.20	1.00 E-5

Table 2. Steel Properties

Yield Strength, f_y	Modulus of Elasticity, E_s
MPa	(MPa)
420	200000

Table 3. Post-Tension Strand Properties

Ultimate Tensile Strength, f_{pu}	Modulus of Elasticity, E_s	Yield Strength, f_{py}
MPa	(MPa)	MPa
1860	200000	1674

Prestressing Force	Friction Coefficient	Wobble Coefficient
MPa	-	(1/m)
1395	0.18	0.002

2.5. Modeling Methodology

Bridge decks were modeled by using MIDAS Civil software. Modeling method was selected as frame analysis. Two elastomeric bearings definition at each axis are included in the model as link elements. Link mechanical properties are calculated and assigned as their real values. Decks were modeled regarding to real geometries. Two main sections, voided and filled type, were defined to represent deck sections. At abutment and pier axis, a filled region is assigned to resist shear forces and the other sections are defined as voided slab to reduce self-weight. Boundary conditions are defined with two types of supports. At one axis, translations and rotations are fixed at all directions. At the other axis, only longitudinal translation is defined as free. Node local axis was same as global axis: X along longitudinal axis, Y along Transverse axis, Z along vertical. Elements are defined from their top center points.

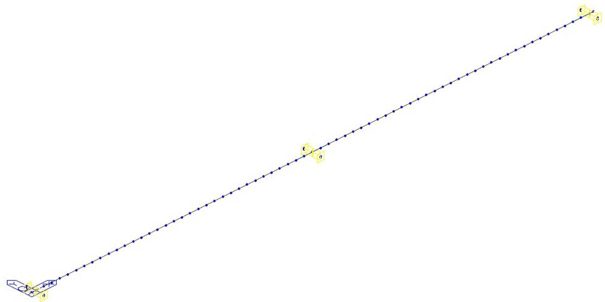

Figure 2. View of Frame Geometry

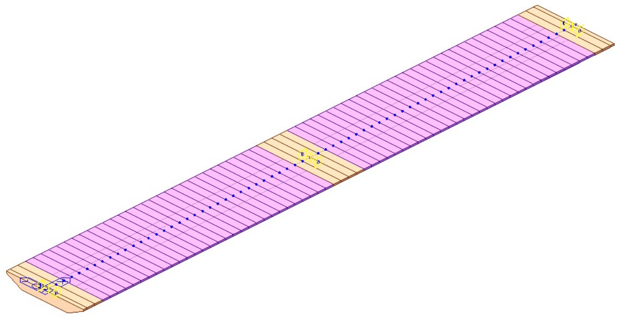

Figure 3. View of 3D Deck Geometry

2.6. Actions on Structure

2.6.1. Permanent Actions

Self-Weight, DC: Self-weight of the deck was considered in the structural loading by setting out concrete unit weight as 25.0 kN/m^3.

Additional Dead Loads, DW: Asphalt, sidewalk and railing loads were calculated as superimposed dead loads and applied to the analysis as external loads. In asphalt and sidewalk loads calculations, width and depth parameters were used with combination of accepted unit weights. Railing loads were taken from specifications as 1.50 kN/m.

Prestressing Force: Prestressing tendons are stressed with 1395 N/mm^2 force from two ends at the same time.

2.6.2. Transient Actions

HL-93 vehicular live loading was used in analysis for two lanes bridge deck. HL-93 loading consists of design truck / design tandem (whichever governs) plus lane load.

Design Truck, LL: Design truck loading schema was given in figure below. Axle load P1 equals to 35 kN and P2 & P3 axles equal to 145 kN each. Spacing between front axles is 4.30 m while rear axis spacing varies 4.30 to 9.00 m. Lane load, W is a uniformly distributed load over 3.00 m. widths as 9.34 kN/m.

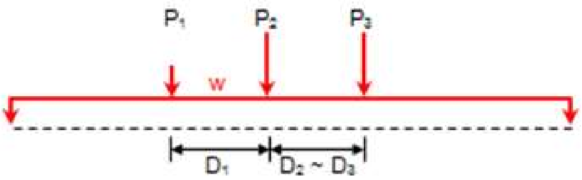

Figure 4. HL-93 Design Truck Loading

Design Tandem, LL: Design tandem consists of a pair of 110 kN axles spaced 1.20 m. apart. The transverse spacing of wheels is 1.80 m. Design lane load is also a requirement in design tandem loading.

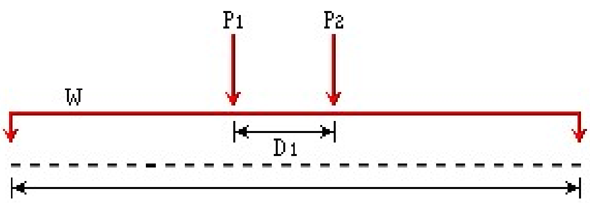

Figure 5. HL-93 Design Tandem Loading

Dynamic load allowance was selected as 33 % for deck component. Multiple presence factor was used as 1 because of two lanes loading.

Pedestrian Loads, PL: A pedestrian load 3.60 kN/m^2 was applied to all sidewalks and considered simultaneously with the vehicular design live load.

Braking Actions, BR: Braking force consists of two options mentioned below and greater of two was used.

- 25 % of the axles weights of design truck or design tandem,
- 5 % of the design truck + lane load or 5 % of the design tandem + lane load.

Temperature Actions, TU & TG: Temperature actions were applied in combination of the two loading cases which are system temperature changing and section temperature differences. In two cases, both cooling and heating actions were considered. For the first case, initial system temperature was selected as +10ºC and effects of system temperature changes up to +30ºC and -15ºC were investigated. For the second case, top and bottom faces of deck were assigned ±10ºC separately to investigate internal forces due to the section temperature differences.

Wind Actions, WS & WL: Wind actions on structure and on live load were investigated in two loading cases. On structure wind load effect, 1.90 kN/m^2 uniformly distributed load was assigned to the deck height. On live load, 1.46 kN/m^2 uniformly distributed load was assigned to deck total height of deck plus 1.80 m live load height.

2.7. Load Combinations

Service Combinations

Service 1: 1.0DC + 1.0DW + 1.0LL + 1.0BR + 1.0PL + 0.3WS + 1.0WL + 1.0 TU + 0.5TG

Service 2: 1.0DC + 1.0DW + 1.3LL + 1.3BR + 1.3PL + 1.0 TU

Service 3: 1.0DC + 1.0DW + 0.8LL + 0.8BR + 0.8PL + 1.0 TU + 0.5TG

Service 4: 1.0DC + 1.0DW + 0.7WS + 1.0 TU + 1.0TU

Strength Combinations

Strength 1: 1.25DC + 1.5DW + 1.75LL + 1.75BR + 1.75PL + 0.5 TU + 0.5TG

Strength 2: 1.25DC + 1. 5DW + 1.35LL + 1.35BR + 1.35PL + 0.5 TU + 0.5TG

Strength 3: 1.25DC + 1.5DW + 1.40WS+ 0.5 TU + 0.5TG

Strength 4: 1.50DC + 1.50DW + 0.5 TU

Strength 5: 1.25DC + 1.5DW + 1.35LL + 1.35BR + 1.35PL + 0.4WS + 1WL+ 0.5 TU + 0.5TG

Notations

DC: Dead Load of Structural Components and Attachments

DW: Dead Load of Wearing Surfaces and Utilities

SH: Force Effects due to Shrinkage

BR: Vehicular Braking Force

LL: Vehicular Live Load

PL: Pedestrian Live Load

WL: Wind Load on Live Load

WS: Wind Load on Structure

TU: Force Effect due to Uniform Temperature

TG: Force Effect due to Temperature Gradient

2.8. Construction Stages

In the first stage, it is assumed that deck concrete was poured and all prestressing tendons were stressed. Self-weight of the deck and tendon forces were activated at this stage. In order to see the creep and shrinkage activities, additional stages; 100 days, 1000 days, 5000 days and 10000 days were introduced to software. It was figured out that at 10000 days, all losses were almost completed and bridge was in service case.

2.9. Allowable Stress Limits

Table 4. Allowable Stress Limits

Stress Type	First Stage	Service Stage
Compression	**0.45fc'**	**0.60fc'**
	15.75 MPa	21.00 Mpa
Tension	**0.50√fc'**	**0.50√fc'**
	2.95 Mpa	2.95 Mpa

2.10. Modeling of Tendons

For three types of deck analysis, tendons were placed regarding to deck stresses. At mid-span, they were placed at the bottom which was 15 cm away from deck bottom face. At the support regions, they were placed at the top which was 20 cm away from deck top face. Vertical spacing between tendons was 20 cm from center to center. Due to the span length differences in deck types, tendon layouts were slightly different at each type. In plan layout, 7 tendons were located horizontally at web sections and each web had 3 row tendons. Thus, the total number of tendons was 21 at each deck section. Each tendon has a group of strands number that will be compared in this paper. Area of each strand was 150 mm^2. Duct diameter was selected as 120 mm. Tendon layout for longitudinal section, plan view and cross sections are given in figures below.

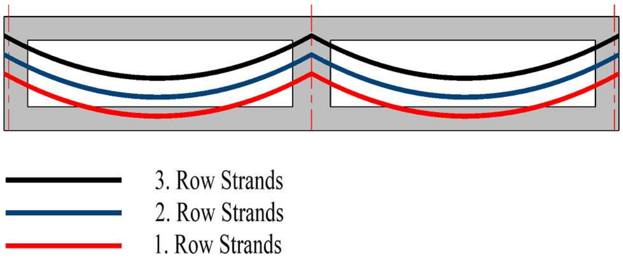

Figure 6. Strands Longitudinal Section Layout

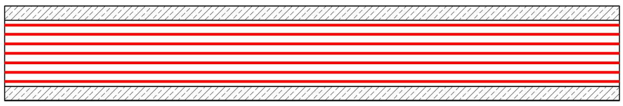

Figure 7. Strands Plan Layout

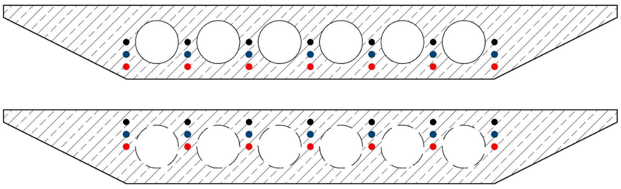

Figure 8. Mid-Span and Diaphram Sections

At each deck type analysis, 4 different strand area were controlled. Stress comparison results were given in tabular form and in graphs.

Table 5. Used Strand Numbers for Deck Types

Span Length	1. Step	2. Step	3. Step	4. Step
(m)	# of St.	# of St.	# of St.	# of St.
2 x 32	17	19	21	23
2 x 34	19	21	23	25
2 x 36	21	23	25	27

2.11. Interaction Between Deck Stresses and Strand Numbers

In stress results, (-) sign represents compression while (+) sign represents tension.

2.11.1. Deck Type 1 (2x32.00 m.)

Table 6. Deck Stresses for Type 1

Stage	Deck Face	17 St.	19 St.	21 St.	23 St.
		(Mpa)	(Mpa)	(Mpa)	(Mpa)
First	Top	-11.08	-12.48	-13.58	-14.80
	Bottom	-10.44	-12.33	-14.50	-16.50
Service	Top	3.17	1.73	0.33	0
	Bottom	-15.75	-15.43	-15.12	-14.83

At deck type 1, number of strands used 19 and 21 satisfies all stress limits for the first stage and service stage. At 17 strands check, at the top face of the pier axis, tension stress was obtained as 3.17 MPa that exceeds the tension stress capacity limit at service stage. At 23 strands check, at the bottom face of the mid-span, compression stress was obtained as 16.50 MPa which also exceeds the 15.75 MPa compression stress capacity at the first stage when self-weight and tendon forces were activated. Hence, step 1 and 4 (17 & 19 strands) are not acceptable regarding to stress capacity limits. Step 2 (19 strands) is the most reasonable choice for the design of deck type 1. Above mentioned values are given in graph below in order to be more representative.

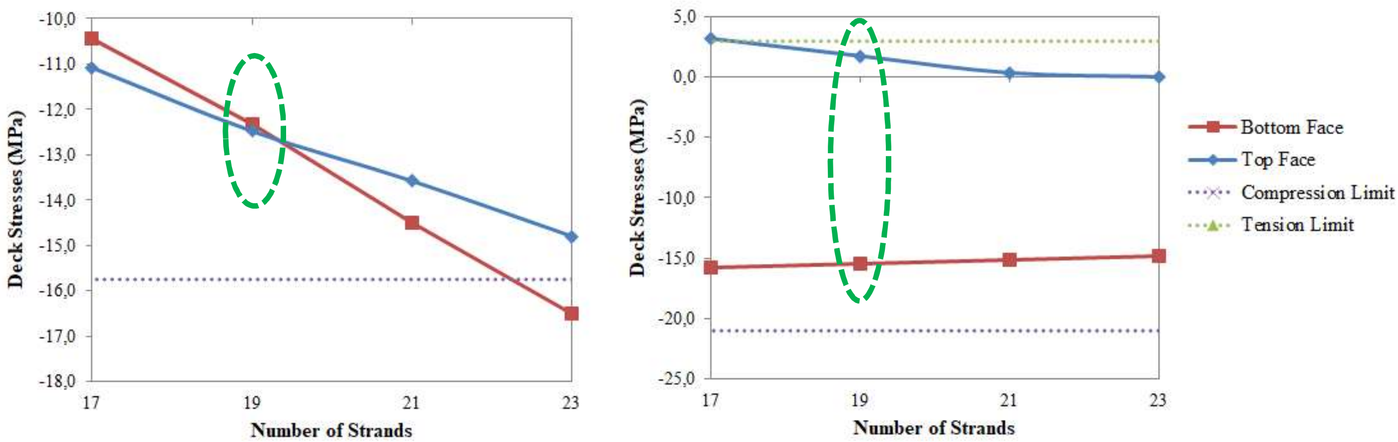

Figure 9. Deck Type 1, Stresses vs. Strands Graph (First Stage & Service Stage, Respectively)

2.11.2. Deck Type 2 (2x34.00 m.)

Table 7. Deck Stresses for Type 2

Stage	Deck Face	19 St.	21 St.	23 St.	25 St.
		(Mpa)	(Mpa)	(Mpa)	(Mpa)
First	Top	-12.35	-13.59	-14.83	-16.05
	Bottom	-11.55	-13.58	-15.58	-17.55
Service	Top	3.76	2.35	0.99	0.34
	Bottom	-17.69	-17.38	-17.09	-16.80

At deck type 2, number of strands used 21 and 23 satisfies all stress limits for the first stage and service stage. At 19 strands usage, top face tension stress exceeds the limits. At 25 strands usage, top and bottom face compression stress exceeds the compression stress capacity at the first stage. Hence, step 1 and 4 (19 & 25 strands usages) are not acceptable regarding to stress capacity limits. Step 2, 21 strands usage is the most reasonable choice for the design of deck type 2. Above mentioned values are given in graph below in order to be more representative.

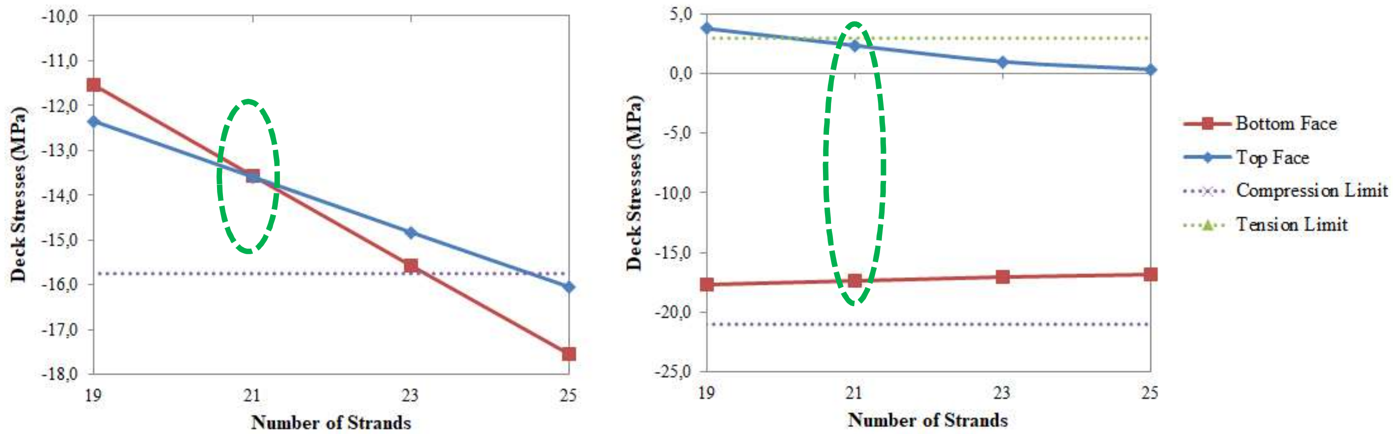

Figure 10. Deck Type 2, Stresses vs. Strands Graph (First Stage & Service Stage, Respectively)

2.11.3. Deck Type 3 (2x36.00 m.)

Table 8. Deck Stresses for Type 3

Stage	Deck Face	21 St.	23 St.	25 St.	27 St.
		(Mpa)	(Mpa)	(Mpa)	(Mpa)
First	Top	-13.74	-15.21	-15.68	-18.21
	Bottom	-12.65	-14.67	-15.20	-18.61
Service	Top	4.98	3.66	2.36	1.09
	Bottom	-20.32	-20.08	-19.84	-19.70

At deck type 3, number of strands used 25 satisfies all stress limits for the first stage and service stage. In other iterations, compression and tension stress limit problems occur. When using 21 or 23 strands, tension stress exceeds the limits for service stage. At 27 strands usage, compression stress exceeds the limits at the first stage. Hence, step 1, 2 and 4 are not acceptable regarding to stress capacity limits. Only step 3, 25 strands usage is suitable for the design of deck type 4. Above mentioned values are given in graph below in order to be more representative.

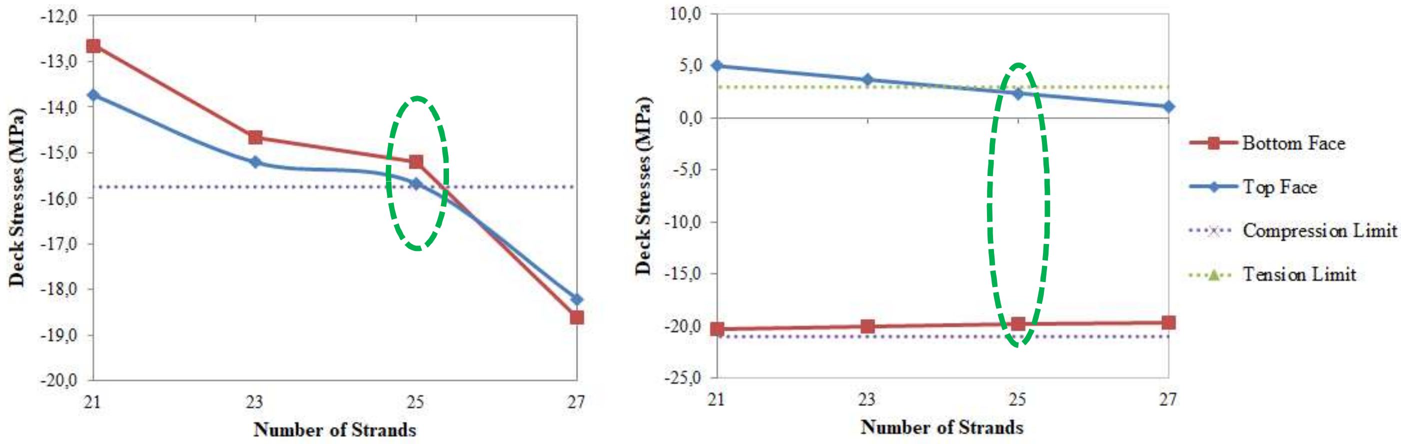

Figure 11. Deck Type 3, Stresses vs. Strands Graph (First Stage & Service Stage, Respectively)

2.12. Results

Decks that have three different span lengths were analyzed. The optimum number of strand for each type was decided. As indicated figure below, number of strand and span lengths are almost directly proportional.

Table 9. Calculated Optimum Strand Number for Deck Types

	Type 1	Type 2	Type 3
	2x32 m	2x34 m	2x36 m
Calculated Strand Number	19	21	25

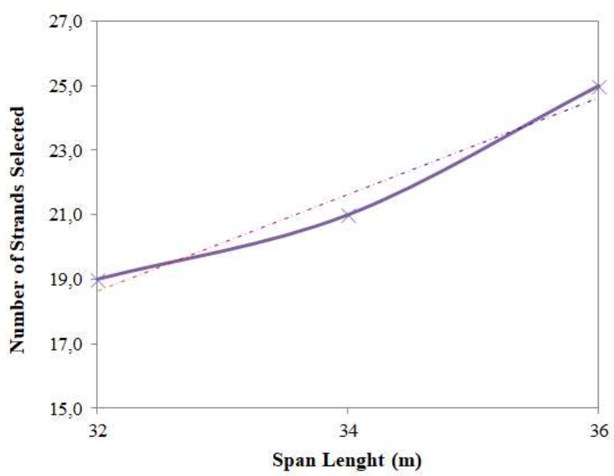

Figure 12. Span Lengths vs. Strands Graph

In type 1 analysis, obtained deck compression and tension stresses are 21 % and 42 % far from the capacity limits. Since there exists a reasonable gap between load and capacity, any optimization techniques can be investigated for this design. Changing deck elements with thinner sections, minimizing tendon diameters, decreasing material strengths can be studied on this deck type.

In type 2 analysis, ratios between loads and capacities are 14 % and 20 % for compression and tension, respectively. Design is reasonable for this type. Adequate capacity limits are available.

In type 3 analysis, mentioned ratios are 0.44 % and 19 % for compression and tension, respectively. For the given tendon layout and 36 m. span length, typical section works at the upper limits. Any improvement can be studied on design. Two important and the convenient improvement techniques are changing material properties and changing tendon layout. Increasing material strength is a good way to enhance stress limits. Tendon longitudinal profile also affects deck stress. While center of the tendons pass through deck peak stress points, this will lead to increase deck capacity. To shift tendon center to the faces, strands can be sidled by bundling.

About tendon optimization issue, three main topics were observed during calculations which are tendon longitudinal layout, initial tendon stress and tendon stress application prioritize. For the whole analysis models, above mentioned topics were investigated cautiously.

Tendon horizontal layout did not affect the stress distribution in analyses since decks were regular; in alignment and not skewed. However, tendon longitudinal layout affects stress distribution significantly. By much iteration, peak stress points were detected. Hence, tendon profile was decided by compound of peak values.

Initial tendon stresses were given 0.75 x f_{pu} by specification. Thus, it is all about tendon type. As the initial force increases, deck tension stresses decrease which is a preferred case mostly by the designer. However, first stage compression limits should be checked if initial tendon force increases.

Stressing tendons from both ends at the same time is a good way which causes low stresses because elastic deformation loss occurs only once at the first time.

To conclude, this research focused on PT concrete bridge decks and tendon usage. It is found out that many parameters affect the system solution which can show differences among designers. The objective procedures developed herein is to minimize the tendon number by choosing them in the most convenient way which leads to decrease the construction cost. Reaching the most suitable conditions safely and performing these conditions with lower costs can be named as the "best" design.

Research and Publication Ethics

This paper has been prepared within the scope of international research and publication ethics.

Ethics Committee Approval

This paper does not require any ethics committee permission or special permission.

Conflict of Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

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