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Comparative Study of Pre-tensioning and Post-tensioning Techniques in Prestressed Concrete: A Case Study of a Bridge Project in Tripoli

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مقارنة بين تقنيتي الشدّ المسبق والشدّ اللاحق في الخرسانة سابقة الإجهاد: دراسة حالة لمشروع جسر في طرابلس

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Abstract
Prestressed concrete technology is an advanced structural solution designed to enhance the mechanical performance of concrete elements and mitigate cracking and deflection caused by service loads. This technique relies on inducing internal compressive stresses to counteract tensile stresses during service, thereby improving durability, stiffness, and structural longevity.
This study explores the fundamental principles of prestressed concrete, highlighting the distinctions between pre-tensioning and post-tensioning regarding execution and application. It features a case study of a concrete bridge in Tripoli implemented via post-tensioning. The analysis is based on technical data from the executing company, including geometric dimensions, concrete properties, and prestressing tendon specifications.
Results indicate that post-tensioning significantly improved the bridge's structural behavior by reducing tensile stresses and cracking while increasing load-bearing capacity. The study achieved both structural and economic efficiency suitable for the project's requirements. In conclusion, post-tensioning proves to be a reliable and effective choice for concrete bridge design, especially for long-span projects under variable environmental and operational conditions.

Keywords: Prestressed Concrete, Post-tensioning, Pre-tensioning, Bridges, Structural Performance, Tensile Stress,

الملخص
تُعد تقنية الخرسانة مسبقة الإجهاد أحد الحلول الإنشائية المتقدمة الرامية إلى تحسين الأداء الميكانيكي للعناصر الخرسانية، والحد من ظواهر التشقق والترخيم الناتجة عن الأحمال التشغيلية. تعتمد هذه التقنية على توليد إجهادات ضغط داخلية في الخرسانة لموازنة إجهادات الشد المتولدة أثناء الخدمة، مما يعزز من متانة المنشأ وصلابته ويرفع من عمره الافتراضي.
تستعرض هذه الدراسة المبادئ الأساسية للخرسانة مسبقة الإجهاد، مع تبيان الفروق الجوهرية بين طريقتي الشد المسبق والشد اللاحق من حيث آليات التنفيذ ومجالات التطبيق. كما تتضمن الورقة دراسة حالة لجسر خرساني بمدينة طرابلس نُفذ

باستخدام تقنية الشد اللاحق؛ حيث استند التحليل إلى البيانات الفنية الواردة من الشركة المنفذة، بما في ذلك الأبعاد الهندسية، ورتبة الخرسانة، ومواصفات كابلات الإجهاد.
أظهرت النتائج أن استخدام الشد اللاحق ساهم بفاعلية في تحسين السلوك الإنشائي للجسر عبر تقليل إجهادات الشد والتشققات المتوقعة، ورفع قدرة التحمل، بالإضافة إلى تحقيق كفاءة إنشائية واقتصادية تلبّي متطلبات المشروع. وتخلص الدراسة إلى أن الشد اللاحق يمثل خياراً فعالاً وموثوقاً في تصميم وتنفيذ الجسور، لا سيما في المشاريع ذات البحور الكبيرة والظروف البيئية والتشغيلية المتغيرة.

الكلمات المفتاحية: الخرسانة مسبقة الإجهاد، الشد اللاحق، الشد المسبق، هندسة الجسور، الأداء الإنشائي، إجهادات الشد.

Introduction

Concrete is one of the most widely used materials in construction and structural engineering due to its high compressive strength; however, its tensile strength remains relatively limited compared to other structural materials. This deficiency led to the development of prestressed concrete technology, which has become an advanced structural solution increasingly applied in modern projects, including several structures implemented within Libya.

The technique of prestressing relies on introducing initial compressive stresses into the concrete element. These stresses counteract or reduce the tensile stresses generated by operational loads, thereby enhancing structural performance and minimizing the likelihood of cracking. This technology is built upon various scientific and engineering foundations, integrating material mechanics, structural analysis, and advanced execution techniques, making it more complex than conventional reinforced concrete.

Prestressed concrete is classified into two primary methods:

- Pre-tensioned Concrete.
- Post-tensioned Concrete.

Both methods aim to enhance tensile resistance and structural efficiency, providing a clear advantage in applications involving large spans and heavy loads. Consequently, prestressed concrete serves as a fundamental pillar of modern construction due to its structural efficiency, economic viability, and long-term sustainability.

Problem Statement

The central challenge lies in the trade-off between pre-tensioning and post-tensioning techniques when designing major concrete structures. While pre-tensioning is generally preferred for precast elements, post-tensioning becomes essential for projects characterized by structural complexity and long spans. Selecting the most appropriate technique depends on a set of engineering constraints and execution conditions that require rigorous analysis to ensure structural safety and operational efficiency

Study Objectives

The objective of this study is to conduct a comprehensive technical comparison between pre-tensioning and post-tensioning techniques. This is done to determine the optimal structural choice for a bridge project in Tripoli, while analyzing how well the selected technique aligns with the project's engineering requirements

Significance of the Study

This study provides a scientific reference to support engineering decision-making when selecting prestressing systems. This contributes to enhancing the efficiency of concrete structures and mitigating structural risks resulting from inaccurate technical choices, thereby ensuring the sustainability of infrastructure in Tripoli and achieving the desired economic and structural feasibility.

Concept of Prestressed Concrete

Prestressed concrete represents a fundamental engineering evolution beyond conventional reinforced concrete. The philosophy of this system focuses on generating intentional internal compressive stresses within the structural element before it is subjected to operational loads [1].

This is achieved by stretching high-strength cables to stress levels typically reaching 70% of their ultimate strength before transferring the load to the element. This technology enables the optimal utilisation of high-performance materials, including concrete with compressive strengths exceeding 40 MPa and prestressing steel with tensile strengths of up to 1860 MPa. This integration improves both strength and serviceability, enabling the construction of long spans and complex structures with slender, lightweight cross-sections.

Materials Specifications

High-strength concrete is essential for ensuring efficient force transfer from the tendons to the structural element. It must possess:

- High Early Compressive Strength: To withstand concentrated stresses during anchoring and allow for early force transfer.
- Volumetric Stability: To minimize creep and shrinkage, thereby reducing prestress losses.
- High Modulus of Elasticity: To limit instantaneous elastic strain during force transfer.

According to ACI 318-19, prestressed concrete strength typically ranges between 35 MPa and 70 MPa.
Regarding the steel [2], the transition to high-strength steel was the decisive factor in the success of prestressing. The tendons used include [3]:

- Wires: Cold-drawn carbon steel wires (5 mm to 8 mm diameter) with tensile strengths up to 1700 MPa.
- Strands: The most common type, usually consisting of 7 wires with an ultimate strength of 1860 MPa (Grade 270).
- Prestressing Bars: Alloy steel bars (20 mm to 50 mm diameter) used for short post-tensioning applications, with strengths around 1035 MPa.

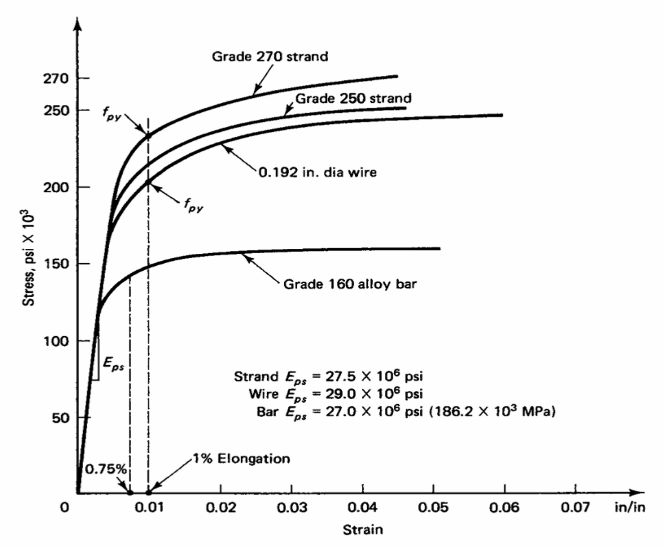

Figure 1: The Stress-Strain Curve for Prestressing Steel.

Pre-stress Techniques

1- Pre-tensioning: Commonly performed in manufacturing plants

- Tendons are tensioned between two abutments using hydraulic jacks.
- Concrete is cast around the tensioned tendons.
- Once concrete reaches the required strength (at least 28 MPa or 70% of $f'c$), tendons are gradually released.
- Forces are transferred to the concrete via bond

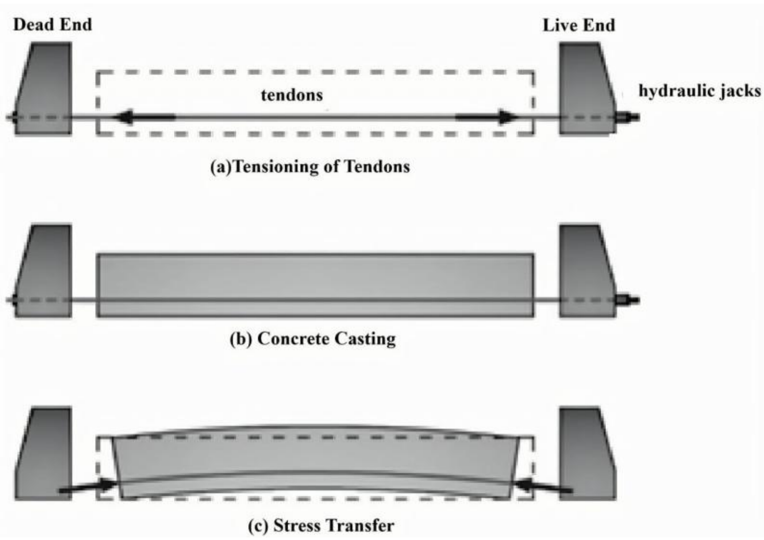

Figure 2: stages of the pre-tensioning process.

2- **Post-tensioning**: Applied in-situ (on-site), offering high flexibility

- Ducts follow draped profiles within the formwork before casting.
- After concrete hardens (30-35 MPa), tendons are tensioned and anchored against anchor plates.
- Bonded Systems: Ducts are filled with cementitious grout for protection and bonding.
- Unbonded Systems: Tendons remain free to move, coated with grease and protective sheathing.

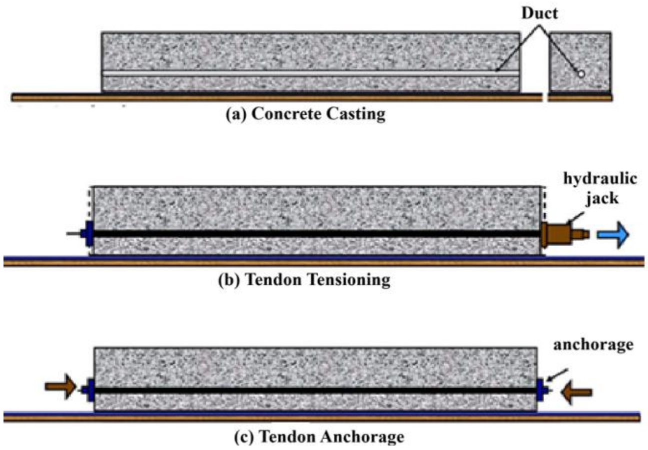

Figure 3: stages of the post-tensioning process.

"Stress distribution is based on the principle of superposition according to the theory of elasticity, where eccentric compressive stresses are combined with bending stresses resulting from loads."

$$\sigma = -\frac{P}{A} \pm \frac{P.e}{S} \pm \frac{M}{S_t}$$

Table 1: Allowable permissible stress ACI-19 code.

Immediately after prestress transfer (Before losses)		**At the service load (After losses)**	
Extreme fiber stress in compression	$0.6f'_{ci}$	Extreme fiber stress in compression due to prestress and sustain load (part of L.L)	$0.45f'_{c}$
Extreme fiber stress in tension	$0.25\sqrt{f'_{ci}}$	Extreme fiber stress in compression due to prestress and total load	$0.6f'_{c}$
Extreme fiber stress in tension at ends of simply supported members	$0.5\sqrt{f'_{ci}}$	Extreme fiber stress in tension	$0.5\sqrt{f'_{c}}$
Extreme fiber stress in compression at ends of simply supported members	$0.7f'_{ci}$		

Where:
f'_{ci} =compressive strength of concrete at the time of initial prestress
f'_{c} =specified compressive strength of concrete

To calculate the actual stresses during the transfer stage, the following equations are used

$$(\sigma_{top})_i = -\frac{P_i}{A} + \frac{P_i \cdot e}{S_t} - \frac{M_{ow}}{S_t}$$

$$(\sigma_{bot})_i = -\frac{P_i}{A} - \frac{P_i \cdot e}{S_b} + \frac{M_{ow}}{S_b}$$

To calculate the actual stresses during the service stage, the following equations are used:

$$\sigma_{top} = -\frac{P_e}{A} + \frac{P_e \cdot e}{S_t} - \frac{M_{service}}{S_t}$$

$$\sigma_{top} = -\frac{P_e}{A} - \frac{P_e \cdot e}{S_b} + \frac{M_{service}}{S_b}$$

Prestress Losses in Prestressing Steel
Prestressing force undergoes a gradual reduction over time, starting from the stage of load transfer, due to various factors that differ based on the tensioning method

- Prestress Losses in Pre-tensioned Elements

Loss due to Elastic Shortening of Concrete	$\Delta f_{pES} = \frac{E_p}{E_{ci}} \cdot f_{cgp}$
Loss due to Concrete Shrinkage	$\Delta f_{pSR} = \varepsilon_{sh} \cdot E_p \cdot K_{sh}$
Loss due to Concrete Creep	$\Delta f_{pCR} = \frac{E_p}{E_c} \cdot \psi_{cr} \cdot f_{cgp}$
Loss due to Steel Relaxation	$\Delta f_{pR} = f_{pi} \cdot \left(\frac{\log(t)}{45}\right) \cdot \left(\frac{f_{pi}}{f_{py}} - 0.55\right)$
Creep and Relaxation Interaction	$\left(\Delta f_{pCR} + \Delta f_{pR}\right)_{Int} = \left(20 - 0.4 \cdot \Delta f_{pES}\right) + 7$
Total Prestress Losses	$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + (\Delta f_{pCR} + \Delta f_{pR})_{Int}$

- Prestress Losses in Post-Tensioned Elements

Loss due to Friction	$\Delta f_{pF} = f_{cgp}\left(1 - e^{-(k \cdot x + \mu \cdot \alpha)}\right)$
Loss due to Anchorage Slip	$\Delta f_{pA} = \frac{2 \cdot \delta \cdot E_p}{L}$
Loss due to Elastic Shortening of Concrete	$\Delta f_{pES} = \frac{n-1}{2n} \cdot \frac{E_p}{E_{ci}} \cdot f_{cgp}$
Loss due to Concrete Shrinkage	$\Delta f_{pSR} = \varepsilon_{sh} \cdot E_p \cdot K_{sh}$
Loss due to Concrete Creep	$\Delta f_{pCR} = \frac{E_p}{E_c} \cdot \psi_{cr} \cdot f_{cgp}$
Loss due to Steel Relaxation	$\Delta f_{pR} = f_{pi} \cdot \left(\frac{\log(t)}{40}\right) \cdot \left(\frac{f_{pi}}{f_{py}} - 0.55\right)$
Creep and Relaxation Interaction	$\left(\Delta f_{pCR} + \Delta f_{pR}\right)_{Int} = \left(20 - 0.4 \cdot \Delta f_{pES}\right) + 7$
Total Prestress Losses	$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + (\Delta f_{pCR} + \Delta f_{pR})_{Int}$

Where:

E_p	Modulus of Elasticity of Prestressing Steel	ψ_{cr}	Creep Coefficient
E_{ci}	Modulus of Elasticity of Concrete at Transfer	E_c	Modular Ratio
f_{cgp}	Stress in Concrete at the C.G.S. (Center of Gravity of Steel)	t	time
ε_{sh}	Ultimate Shrinkage Strain of Concrete	f_{pi}	Initial Prestressing Stress
K_{sh}	Section Modulus	f_{py}	Yield Strength of Prestressing Steel
k	Wobble Friction Coefficient	x	Length of Tendon from the Jacking End
μ	Curvature Friction Coefficient	α	Cumulative Angle of Curvature
δ	Anchorage Slip Magnitude	L	Total Tendon Length
n	Total Number of Tendons/Strands		

Structural Analysis and Case Study

Analysis involves two critical stages:

- the Transfer Stage (early age, initial force Pi
- the Service Stage (after time-dependent losses, effective force Pe

Case Study: Tripoli Bridge Project
The project involves a bridge at Al-Farnaj, Tripoli, consisting of 7 spans, each 27.4 meters long

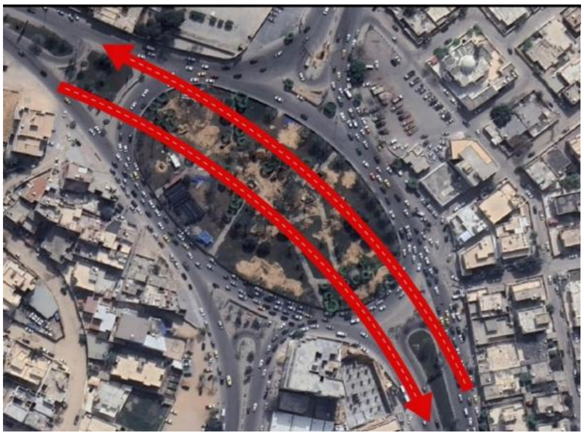

Figure 4 :Illustrates the alignment of the proposed bridge

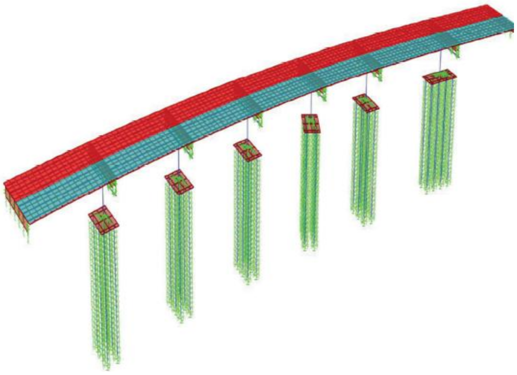

Figure 5 :Simulation of the bridge geometry

$$W_D = 32.22\ KN\backslash m^2 \quad W_L = 3140.64\ KN$$
$$L = 27400\ mm \quad A = 511270\ mm^2$$
$$e = 300\ mm \quad f_{pu} = 1860\ MPa$$
$$A_{strand} = 150\ mm^2$$
$$, E_p = 195000\ MPa \quad E_{ci} = 33000MPa$$
$$, P_{i,post} = 1800\ KN \quad P_{i,pre} = 3300\ KN$$
$$f'c = 70\ MPa\ , f'ci = 55\ MPa$$
$$M_{ow} = 250\ KN.m,\ M_T = 662\ KN.m$$
$$S_b = 71900000\ mm^3, S_t = 78800000\ mm^3$$

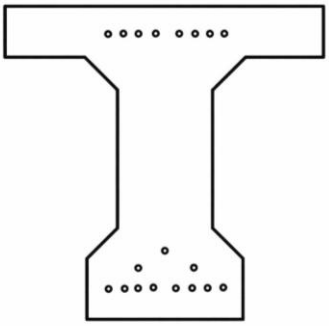

Figure 6: cross-section of pre-stressed beam.

Project Data Obtained from the Supervisor

1. Pre-tensioning Method

- Calculation of Losses:

$$\Delta f_{pES} = \frac{195000}{33000} \times 12 \quad = 70.9\ MPa$$
$$\Delta f_{pSR} = 0.0003 \times 195000 \times\ 1.0 \ = 58.5\ MPa$$
$$\Delta f_{pCR} = \frac{195000}{33000} \times 2.0 \times\ 12 = 141.8\ MPa$$
$$\Delta f_{pR} = 1395 \times \left(\frac{\log(50)}{45}\right) \times \left(\frac{1395}{1674} - 0.55\right) = 14.92\ MPa$$
$$\Delta f_{pT} = 70.9 + 58.5 + 141.8 + 14.92 = 286.12\ MPa$$

- Pre-tensioning Loss Percentage:

$$\frac{286.12}{1860} \times 100 = 15.4\%$$

- Number of Strands/Wires:

$$f_{pi,pre} = r_{pre} \times f_{pu} = 0.85 \times 1860 = 1581\ MPa$$
$$P_{strand,pre} = A_{strand} \times f_{pi,pre} = 150 \times 1488 \times 10^{-3} = 237.15\ KN$$
$$n_{pre} = \frac{P_{i,pre}}{P_{strand,pre}} = \frac{3300}{223.2} = 13.91 \ \approx 14$$
$$P_e = 0.85 \times 3300 = 2805\ KN$$

Stress Calculation and Verification:

- Allowable Stresses at the Transfer Stage**:**

$$(\sigma_{top})_i \leq 0.5\sqrt{f'ci} = 0.5 \times \sqrt{55} = 3.71\ MPa$$

$$(\sigma_{bot})_i \leq 0.7 \times f'ci = 0.7 \times 55 = 38.5\ \text{MPa}$$

$$(\sigma_{top})_i = -\frac{3300}{511270} + \frac{3300\ \times 10^3 \times 300}{78800000} - \frac{250 \times 10^6}{78800000}$$

$$(\sigma_{top})_i = 9.38\ \text{MPa (Tension)}\ \geq 3.71\ \text{MPa. unsafe}$$

$$(\sigma_{bot})_i = -\frac{3300}{511270} - \frac{3300 \times 10^3 \times 300}{71900000} + \frac{250 \times 10^6}{71900000}$$

$$(\sigma_{bot})_i = 10.30\ \text{MPa (Compression)}\ \leq\ 38.5\ \text{MPa}$$

Due to the structural failure of the section during the load transfer stage, it will not proceed to the service stage. Consequently, there is no requirement to verify service stage conditions, as the pre-tensioning system has been proven unsuitable for this specific application

2. Post-tensioning Method

- Calculation of Losses:

$$\Delta f_{pF} = 1860 \times \left(1 - e^{-(0.005\times12+0.18\times0.1)}\right) = 139.7\ \text{MPa}$$

$$\Delta f_{pA} = \frac{2 \times 6 \times 195000}{27400} = 85.4\ \text{MPa}$$

$$\Delta f_{pES} = 0.46 \times \frac{195000}{33000} \times 12 \ = 32.9\ \text{MPa}$$

$$\Delta f_{pSR} = 0.0003 \times 195000 \times\ 0.8\ = 46.8\ \text{MPa}$$

$$\Delta f_{pCR} = \frac{195000}{33000} \times 1.5 \times\ 12 = 106.36\ \text{MPa}$$

$$\Delta f_{pR} = 1395 \times \left(\frac{\log(50)}{40}\right) \times \left(\frac{1395}{1674} - 0.55\right) = 16.78\ \text{MPa}$$

$$\Delta f_{pT} = 139.7 + 85.4 + 32.9 + 46.8 + 106.36 + 16.78 = 427.94\ \text{MPa}$$

- Post-tensioning Loss Percentage:

$$\frac{427.94}{1860} \times 100 = 23\%$$

- Number of Strands/Wires:

$$f_{pi,post} = r_{post} \times f_{pu} = 0.77 \times 1860 = 1432\ \text{MPa}$$

$$P_{strand,post} = A_{strand} \times f_{pi,post} = 150 \times 1432 \times 10^{-3} = 214.8\ \text{KN}$$

$$n_{pre} = \frac{P_{i,post}}{P_{strand,post}} = \frac{1800}{195.3} = 8.4\ \approx 9$$

$$P_e = 0.77 \times 1800 = 1386\ \text{KN}$$

Stress Calculation and Verification:

- Allowable Stresses at the Transfer Stage**:**

$$(\sigma_{top})_i \leq 0.5\sqrt{f'ci} = 0.5 \times \sqrt{55} = 3.71\ \text{MPa}$$

$$(\sigma_{bot})_i \leq 0.7 \times f'ci = 0.7 \times 55 = 38.5\ \text{MPa}$$

$$(\sigma_{top})_i = -\frac{1800}{511270} + \frac{1800 \times 10^3 \times 300}{78800000} - \frac{250 \times 10^6}{78800000}$$

$$(\sigma_{top})_i = 3.67\text{MPa (Tension)}\ \leq 3.71\ \text{safe}$$

$$(\sigma_{bot})_i = -\frac{1800}{511270} - \frac{1800 \times 10^3 \times 300}{71900000} + \frac{250 \times 10^6}{71900000}$$

$$(\sigma_{bot})_i = 4.04 \text{ MPa (Compression)} \leq 38.5 \text{ MPa Safe}$$

- Allowable Stresses at Service Stage

$$\sigma_{top} \leq 0.5 \times f'c = 0.5 \times 70 = 35 \text{ MPa}$$

$$\sigma_{bot} \leq 0.6 \times f'c = 0.6 \times 70 = 42 \text{ MPa}$$

$$\sigma_{top} = -\frac{1386}{511270} + \frac{1386 \times 10^3 \times 300}{78800000} - \frac{662 \times 10^6}{78800000}$$

$$\sigma_{top} = 3.12 \text{ (Compression)} \leq 35 \text{ safe}$$

$$\sigma_{bot} = -\frac{1386}{511270} - \frac{1386 \times 10^3 \times 300}{71900000} + \frac{662 \times 10^6}{71900000}$$

$$\sigma_{bot} = 3.42 \text{ MPa (Tension)} \leq 42 \text{ MPa safe}$$

Results and discussion

- Pre-Tensioning System

The stress analysis at the transfer stage revealed that most fiber stresses remained within allowable limits. However, the stress at the top fibers of the section approached the permissible threshold, remaining slightly below the maximum allowable value. Although this condition does not violate code requirements and is therefore considered structurally safe, it indicates a relatively critical stress state.
Given that the transfer-stage stresses governed the design and no code violation was observed, the service-stage stress analysis was not pursued for this system within the scope of this study.
This behavior can be attributed to the early transfer of prestress forces to the concrete, combined with the effects of self-weight during handling and transportation, which may induce unfavorable tensile stresses at the top fibers.

- Post-Tensioning System

In contrast, the post-tensioning system demonstrated a more favorable stress distribution. All stresses at both the transfer and service stages were found to be within allowable limits, with adequate margins of safety at the top and bottom fibers.
The improved performance is primarily due to the delayed application of prestress forces and the flexibility in tendon profiling, which allows for better balancing of internal moments caused by self-weight and external loads.

Comparative Analysis

The fundamental difference between the two systems lies in the timing and controllability of prestress application. While pre-tensioning introduces prestress at an early age with limited flexibility, post-tensioning allows for optimized force application aligned with actual loading conditions, resulting in improved stress control and overall structural efficiency.

Table 2: Comparison Between Pre-tensioning and Post-tensioning in Prestressed Concrete.

Item	Pre-tensioned Concrete	Post-tensioned Concrete
Place of Execution	In precast factories	in-site (Greater flexibility)
Construction Method	Tensioning tendons before casting and anchoring them until concrete reaches the required strength	Casting concrete first, then tensioning tendons after reaching specific compressive strength
Quality Control	High quality due to manufacturing in a controlled environment	Variable (Medium to High) as it depends on site conditions
Prestress Losses	Constant, and lower than post-tensioning	Higher than pre-tensioning, but can be compensated for in the field

Safety and Durability	Higher safety due to factory-controlled conditions	Requires additional safety precautions during site tensioning operations
Maintenance	Difficult access to tendons after casting, complicating maintenance procedures	Easier access to tendons from anchorages, facilitating maintenance
Span Length	Limited due to transportation and handling constraints of precast elements	Flexible and ideal for long spans and complex structural configurations
Durability	Lower durability due to limited crack control and corrosion vulnerability at anchorages	Higher durability due to precise stress control and protection within anti-corrosive sheaths

Conclusion

Based on the analytical results, the following conclusions can be drawn:

- Both prestressing systems satisfy safety requirements at the transfer stage.
- The post-tensioning system provides superior stress performance by maintaining all stresses within allowable limits at both transfer and service stages.
- The pre-tensioning system exhibits greater sensitivity to tensile stresses at the top fibers, particularly during the transfer stage.
- The choice between the two systems should consider not only structural safety but also stress distribution efficiency and serviceability performance

Recommendations

- Post-tensioning is recommended for structural elements where stress control at multiple stages is critical, particularly in deep or non-symmetrical sections.
- When pre-tensioning is adopted, design improvements such as modifying tendon eccentricity, adjusting cross-sectional geometry, or providing supplemental reinforcement should be considered to mitigate critical tensile stresses.
- Service-stage stress analysis is strongly recommended in comparative design studies, even when transfer-stage stresses appear acceptable.
- Future studies should incorporate economic, constructional, and long-term performance aspects to provide a more comprehensive evaluation of prestressing system selection.

Compliance with ethical standards

"The authors acknowledge that the data utilized in this study were provided by the project's supervising engineer and the contracting company, with the permissions for academic publication"

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