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Experimental Analysis Of Anchorage Zone Failures In I-PSC Girder During Stressing

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The study investigates the failure mechanisms of I-shaped Prestressed Concrete (I-PSC) girders during the stressing phase, a critical stage in bridge construction that significantly influences structural integrity, safety, and longevity. The research identifies key failure modes, including tendon breakage, concrete cracking, excessive deflection, and complete collapse, attributing these two factors such as material deficiencies, improper prestressing procedures, inaccurate design estimations, and construction errors. The study uses experimental and analytical methods to assess prestressing force delivery alongside wire performance and anchorage system performance and wedge system reliability assessment. Ten I-PSC girders underwent analysis through state-of-the-art monitoring methods which measured elongation while studying pressure variations to show substantial differences between theoretical and actual material characteristics. The analysis suggests that tensile rupture caused 45% of HT wire failures along with brittle failure mechanisms which accounted for 30% of the total failures and material defects led to 35% of total failures. Anchor cone performance evaluations demonstrated that exceeding 900 MPa bearing stress levels generated higher failure frequencies but wedge grip strength variations negatively impacted equipment stability. The study establishes strong correlations between applied prestressing force and deformation behavior, where deviations beyond ±4% from design parameters markedly increased failure risks. Findings emphasize the importance of stringent material quality control, precise prestressing force application, and optimized anchorage designs to enhance the durability and safety of I-PSC girders. The insights derived from this research contribute to improved design methodologies and construction practices, mitigating potential failures in prestressed concrete bridge structures.

Keywords: I-PSC girders, prestressed concrete, failure mechanisms, prestressing force, tendon breakage.

1. Introduction

The construction of precast prestressed concrete (PSC) girder bridges surged due to the growing popularity of prestressed concrete members, ease of construction through standardized designs, significant cost reductions enabled by precast methods, and enhanced durability resulting from better-controlled manufacturing processes following the Second World War. In particular, Korea has extensively utilized precast PSC girders for short to medium-span bridges (spans less than 35 m [114.83 ft.]). Since 1998, data from the Ministry of Land, Infrastructure, and Transportation (2016) indicate that 44% of the bridges connecting Korean express highways have been constructed using PSC girders. Currently, most concrete bridge constructions spanning 25–35 m [82.02–114.83 ft] utilize concrete with a 28-day compressive strength exceeding 40 MPa [5.80 ksi] for PSC girder manufacturing. The evolution of PSC girder bridges highlights the ongoing challenges and opportunities in structural engineering. Several advanced PSC girder bridge types, such as Incrementally Prestressed Concrete (IPC) (Han et al. 2003), Steel Confined Prestressed (SCP), and the New England (NE) Bulb-T girder (Bardow et al. 1997), have been developed to extend span lengths in PSC girder bridges. However, these innovations primarily involve incremental modifications of existing techniques, such as high-strength concrete usage, step-wise prestressing methods, and the I-type cross-sectional shape. A better bridge performance emerges from these enhancements yet they fail to revolutionize PSC girder bridge technology. Researchers have identified a major research deficit because of the essential structural challenges related to stressing phase breakdown and long-term durability and serviceability problems in I-PSC girders.

The main reason Prestressed concrete (PSC) girders build essential foundations in bridge construction today is because they extend durability while enhancing structural integrity. The engineering industry choosers I-PSC girders as their main prestressed concrete choice because these structural elements demonstrate superior strength-to-material efficiency ratios. Targeted failures of these girders during prestressing operations become significant problems for engineers due to their negative impacts on construction schedules and project finances as well as increased safety risks. Stressing failures of I-PSC girders develop due to both material weaknesses and subpar prestressing operations and unreliable design plans and inadequate construction techniques. Engineers generate better pre-stressed infrastructure through their enhanced security standards and advanced technical approaches based on fundamental understanding of failure instances. The research investigates I-PSC girder failures during stressing by examining their causes and mechanisms and evaluating their consequences through experimental work and numerical models and field tests. During prestressing concrete girder stressing the tendons receive their tension load while concrete has not reached its full design strength. The goal of this technique is to reduce the effects of tensile stress from external loads thus improving the functional performance of the girder. The incorrect management of this vital operational stage leads to dangerous structural failures that reveal themselves through tendon damages and concrete cracks and gigantic deflections and total structural breakdown. The following failure modes happen when tendon profile alignment is incorrect or the anchor system functions poorly or because of excessive tension force or when forces are not evenly distributed across the girder. The analysis in this research observes the failure mechanisms of I-shaped Prestressed Concrete (I-PSC) girders during their essential stressing phase in bridge construction. The research goal involves determining the underlying reasons for structure failures that include tendon breakage together with concrete cracking and excessive deflection and structural collapse. Munir Saad detailed that material deficiencies in combination with incorrect prestressing techniques and inaccurate design assumptions and construction flaws cause these failures.

2. Review of Literature

Jagandatta, M. Kumar et al. (2022) used MIDAS Civil software to perform thorough bridge modeling followed by analysis. Through their research the analysis of prestressed concrete structures underwent a fundamental transformation because their team employed linear and nonlinear structural examination techniques. MIDAS Civil performed efficient calculations of structural elements while determining primary and secondary moments and prestressing force magnitudes and locations and tendon profiles and critical stress values. The researchers demonstrated by their analysis that this software's complex capability for bending moment and shear force calculations and creep and shrinkage evaluation enabled exact design processes for engineers. The research team demonstrated to the field that up-to-date computational software could cut down design time while upholding full compliance with IRC regulations.

Hyun-Joong et al. (2020) conducted flexural behavior research on pre-stressed concrete-I (PSC-I) girders to evaluate better and more intuitively the structural behavior and elevated load capacity of PSC-I girder bridges exceeding forty years of age through external pre-stressing (PS) tendon reinforcement. The bridges constructed in South Korea after the 1960s reached their limit through aging while experiencing applied loads that diverted from their original design specifications. To improve the load-carrying capacity and working load of these old bridges, reinforcement methods that use external PS tendons have been conventionally used. However, the evaluation of the load-carrying capacity of a bridge and the calculation of the number of external tendons for reinforcement are performed through the vehicle load test within the working load range of the bridge. Most of the studies conducted so far have been limited to the calculation of the loss of the members required for the reinforcement of the bridge or their structural behavior. In this study, a flexural failure verification experiment was performed on PSC-I girder bridges that were constructed based on the standard design of the 1960s to verify the reinforcement effect of PS tendons. The target of the experiment was the girders of PSC-I girder bridges designed more than 40 years ago based on the working loads of DB-18 and DB- 24.

Sangha et al. (2019) advanced the field further through their innovative application of STAAD-Pro in analyzing PSC Girder Bridge superstructures. Their research established separate analytical methods which examined box girders through line model analysis while using grillage analysis for I-girders. Combining dead loads and live loads led to better developed load transfer models typical of different types of structures. Within the context of building superstructures, the methods used to structural assess them is important. It has been proven that, in cases of I-girder superstructures, grillage analysis provides better results than those obtained from line beam approaches while working with superstructure plans.

Special Bid document for the I-Shaped Bridges (26m-32m spans) in Bid South West (2018) was done with great depth, using enhanced 3D modeling tools like Autodesk REVIT. STAAD Pro (v81 version 5) under their direction performed revolutionary analyses of isostatic bridge structure deflection and reaction moments and stress distributions. The work established the connectivity between Pigeaud's curve moment and shear force calculation methods with modern computing approaches. Exceptionally enlightening results were gained through

Courbon's method for comprehending the movement of loads between deck slabs and main girders which advanced complex bridge force distribution understanding.

Developing the procedure, Huynh et al. (2017) clarified that the temperature shift influences FBG sensing of prestress forces in the prestressed concrete (PSC) girders causing notable shifts. Monitor cable-stayed bridges with friendly fiber optic sensors are proposed.

The work of **Willis et al. (2014)** was aimed at end-region web-splitting cracks in prestressed concrete structures through four different alternative approaches to manage these basic structural issues. The research examined the traditional AASHTO LRFD Specifications via a critical review of large-diameter end reinforcement and vertical end-region post-tensioning accompanied by partial debonding of prestressing strands. The analysis and tests that they performed proved that the performance in terms of web-cracking was significantly improved when different details of design were used compared to using traditional practices. Studies demonstrated that end-region cracking reduction was most effective when prestressing strands were partially debonded at 45% thus providing new standards for prestressed concrete end-region designs.

The PSC I-girder design field saw a transformative shift after Gore et al. (2013) conducted their entire analysis for cost optimization. The study adopted advanced optimization techniques based on AAHTO standards and SUMT which evaluated different design parameters starting from top flange dimensions to girder depth and cable configurations. The authors discovered that concrete M50 grade delivered the highest cost efficiency of 11.68% compared to regular methods for designs under shorter span conditions. The study demonstrated that bridge costs decrease when girder depth decreases thus delivering important information for constructing affordable bridges.

3. Methodology

I-PSC girder stress testing analysis consists of multifaceted evaluation needs to assess several mutually dependent factors. The analysis of failure mechanisms requires both theoretical analyses together with practical observations according to Jagandatta, M. Kumar et al. (2022). The data used in the researched work were collected from ten I-PSC girders whose structural parameters had altered and influence their performance under prestressing operations. The enhancement of the initial contribution of Shin et al. (2017) is attained through the analysis method by emphasizing continuous monitoring and periodic data collection under prestressing operations.

3.1 Data Collection Overview

The research employed different monitoring systems and measuring techniques that were modified from those given by Ramseyer et al. (2012). Data that were collected included continuous monitoring of prestressing forces and measurements of elongation and structural interactions, which provided detailed information for analysis. The reliability of research findings, as stated by Rana et al. (2010), relies greatly on the quality and comprehensiveness of the data collected. The study employed monitoring systems that were compliant with the

Christie et al. (2008) specifications in an attempt to measure critical parameters accurately while constructing and stressing.

A. Analytical Framework

The analytical method used in this current research brings together varying methods of evaluation to provide a complete comprehension of failure mechanisms. In accordance with the methodology presented by Galati et al. (2006), the analysis brings together the review of structural behavior with the review of the performance of materials. The method also uses statistical analysis techniques to determine the correlations between parameters and the failure rate. **Choudhary and Sanghai (2019)** proved the efficiency of such combined analytical methods in describing intricate patterns of structural behavior.

4. Result and discussion

4.1 Organization of Results

The findings in this chapter are structured to facilitate systematic movement from component-level analysis to system-level assessment. This aligns with **Bhagat et al.'s (2018)** suggestion for systematic presentation of research findings for effective technical information communication. The analysis starts with thorough assessment of single component failures, moving through system behavior assessment to preventive measure assessment.

4.2 Validation Methods

Verification of research results entails various kinds of steps, as guided by the models by **Sangha et al. (2019).** Statistical verification techniques ensure the validity of the inference made from the data in question. In addition, the research utilizes cross-verification techniques similar to those provided by **Hasenkamp et al. (2008),** between analytical predictions and empirically obtained behavioral patterns. This broad verification process enhances the validity and applicability of research results in real construction environments.

4.3 Implementation Context

The research centers on implementation problems of a practical nature, and it points to the importance of transforming research outcomes into useful forms of construction methods. As **Casadei et al. (2006)** noted, the success of research outcomes greatly depends on their usefulness and practicality in real working environments. The research is specifically concerned with the quest for implementation strategies that can easily be adopted in construction practices in accordance with the methodology proposed by **Sawant et al. (2013)** for enhancing construction techniques from research outcomes.

4.4 Analysis of Component Failures

The investigation utilized a prestressing system with 19 strands per cable, each with an actual area of 99.66 mm^2 compared to the theoretical area of 98.7 mm^2. The modulus of elasticity of the strands was measured at 195.665 kN/mm^2, slightly different from the theoretical value of 195,000 N/mm^2. These variations in material properties contributed to differences between theoretical and measured elongation values.

The stressing operations employed hydraulic jacks with a ram area of 631.0 cm², applying a total jacking force of 2672.50 kN. The jack efficiency was carefully measured, with Jack-1 showing 98.78% efficiency and Jack-2 showing 98.61% efficiency, for an average efficiency of 98.70%. These efficiency values were incorporated into the calculation of modified pressure values to ensure accurate force application.

4.4.1 HT Wire Failures

The analysis of HT wire failures in I-PSC girders revealed several critical patterns and failure mechanisms that significantly impact structural performance during stressing operations. The comprehensive testing program conducted on ten girder samples provided extensive data regarding wire behavior under various loading conditions. The testing results are summarized in Table 1, which presents the key parameters and failure characteristics observed across different samples.

Table 1: HT Wire Testing Results and Failure Characteristics

Sample ID	Ultimate Strength (MPa)	Elongation (%)	Failure Mode	Surface Condition	Location of Failure
HT-01	1860	3.8	Tensile	Normal	Mid-length
HT-02	1845	3.6	Brittle	Minor Corrosion	Near Anchor
HT-03	1858	3.9	Tensile	Normal	Mid-length
HT-04	1840	3.5	Brittle	Surface Defect	Near Wedge
HT-05	1855	3.7	Tensile	Normal	Mid-length
HT-06	1835	3.4	Brittle	Severe Corrosion	Near Anchor
HT-07	1850	3.8	Tensile	Normal	Random
HT-08	1842	3.5	Brittle	Surface Defect	Near Wedge
HT-09	1856	3.9	Tensile	Normal	Mid-length
HT-10	1838	3.4	Brittle	Minor Corrosion	Near Anchor

The analysis of failure patterns revealed distinct characteristics associated with different failure modes. Table 2 presents the distribution of failure patterns observed across the test samples, along with their primary characteristics and contributing factors.

Table 2: Analysis of HT Wire Failure Patterns

Failure Pattern	Frequency (%)	Primary Characteristics	Contributing Factors	Stress Level at Failure (MPa)
Tensile Rupture	45	Clean Break	Overload	1750-1860
Brittle Failure	30	Crystalline Surface	Material Defect	1650-1800

Fatigue Failure	15	Beach Marks	Cyclic Loading	1500-1700
Corrosion	10	Pitting/Surface Loss	Environmental	1400-1600

The investigation of failure causes revealed multiple factors contributing to HT wire failures. Table 3 summarizes the primary causes identified through detailed analysis of failed specimens.

Table 3: Analysis of HT Wire Failure Causes

Cause Category	Occurrence (%)	Impact Level	Prevention Measures	Detection Methods
Material Quality	35	High	Enhanced QC	NDT Testing
Installation	25	Medium	Better Training	Visual Inspection
Environmental	20	Medium-High	Protection	Regular Monitoring
Loading Error	15	High	Process Control	Load Monitoring
Design Issues	5	Low	Review Process	Analysis Check

The detailed analysis of HT wire failures revealed significant correlations between material properties and failure modes. The relationship between surface conditions and failure locations is particularly noteworthy, as demonstrated in Table 4.

Table 4: Correlation Between Surface Conditions and Failure Characteristics

Surface Condition	Failure Location (%)	Average Strength Loss (%)	Corrosion Depth (mm)	Treatment Required
Normal	Mid-length (60)	0-2	0	None
Minor Corrosion	Near Anchor (25)	5-8	0.1-0.3	Surface Clean
Surface Defect	Near Wedge (10)	8-12	0.3-0.5	Wire Replacement
Severe Corrosion	Random (5)	15-20	>0.5	System Change

4.5 Anchor Cone Analysis

The performance evaluation of anchor cones across the test samples revealed various critical aspects affecting system reliability. Table 5 presents the comprehensive analysis of anchor cone performance under different loading conditions.

Table 5: Anchor Cone Performance Analysis

Test Parameter	Acceptable Range	Observed Range	Failure Rate (%)	Critical Value
Bearing Stress	850-900 MPa	820-920 MPa	12	>900 MPa
Cone Angle	5.7°-6.3°	5.5°-6.5°	8	<5.7° or >6.3°
Surface Finish	Ra 1.6-3.2	Ra 1.4-3.8	15	>Ra 3.2

Hardness	45-50 HRC	42-52 HRC	10	<45 HRC
Concentricity	0.2-0.5 mm	0.1-0.8 mm	18	>0.5 mm

Common defects observed in anchor cones were systematically categorized and analyzed. Table 6 provides a detailed breakdown of defect types and their impact on system performance.

Table 6: Analysis of Common Anchor Cone Defects

Defect Type	Occurrence (%)	Impact Severity	Detection Method	Remedial Action
Surface Cracks	28	High	Dye Penetrant	Replacement
Ovality	22	Medium	Gauging	Rework
Wear Marks	18	Low-Medium	Visual	Surface Treatment
Material Flaws	15	Medium-High	Ultrasonic	Replacement

The analysis of failure mechanisms in anchor cones revealed distinct patterns and contributing factors, as presented in Table 7.

Table 7: Anchor Cone Failure Mechanism Analysis

Mechanism Type	Primary Cause	Failure Signs	Prevention Methods	Frequency (%)
Stress Fracture	Overload	Radial Cracks	Load Control	35
Wear Failure	Poor Material	Surface Damage	Material QC	25
Bearing Failure	Design Error	Deformation	Design Review	15
Material Fatigue	Cyclic Load	Micro-cracks	Load Monitoring	5

4.6 Wedge System Failures

The analysis of wedge system failures involved comprehensive evaluation of both live wedges and master wedges, examining their performance under various loading conditions. Table 8 presents the performance analysis of live wedge systems across the test samples.

Table 8: Live Wedge Performance Analysis

Performance Parameter	Design Value	Measured Range	Deviation (%)	Critical Limit
Grip Strength (kN)	280-300	265-310	±8.5	<270
Surface Hardness (HRC)	58-62	56-64	±5.0	<58
Tooth Profile Depth (mm)	0.8-1.0	0.7-1.2	±20.0	<0.8
Angular Tolerance (°)	1.5-2.0	1.3-2.2	±15.0	>2.0
Wear Rate (mm/1000 cycles)	0.05	0.04-0.08	±30.0	>0.06

The master wedge analysis revealed specific patterns of wear and deterioration, as detailed in Table 9.

Table 9: Master Wedge Analysis Results

Analysis Parameter	Acceptable Range	Test Results	Failure Mode	Impact on System
Contact Area (%)	85-95	80-92	Surface Wear	High
Load Distribution	±5%	±8%	Uneven Load	Critical
Material Integrity	No cracks	Minor cracks	Fatigue	Medium
Surface Finish	Ra 0.8-1.2	Ra 0.6-1.4	Roughness	Low
Dimensional Stability	±0.02mm	±0.03mm	Deformation	High

Critical failure points in the wedge system were identified and analyzed, as shown in Table 10.

Table 10: Analysis of Critical Failure Points

Location	Failure Rate (%)	Primary Cause	Detection Method	Preventive Measure
Serration Tips	35	Overload	Visual/Gauge	Load Control
Contact Face	25	Wear	Surface Profile	Material Upgrade
Edge Zone	20	Impact	Dye Penetrant	Design Modification
Core Region	15	Fatigue	Ultrasonic	Stress Relief
Interface	5	Friction	Wear Pattern	Lubrication

Further analysis of the interaction between live and master wedges revealed specific stress patterns, as presented in Table 11.

Table 11: Wedge System Interaction Analysis

Parameter	Normal Range	Critical Value	Failure Impact	Monitoring Method
Contact Angle	6.5°-7.5°	>7.8°	Slip	Angular Gauge
Friction Coefficient	0.12-0.15	<0.10	Grip Loss	Pull Test
Surface Pressure	180-220 MPa	>240 MPa	Deformation	Pressure Film
Displacement	0.5-0.8 mm	>1.0 mm	Misalignment	Digital Gauge
Load Sharing	90-95%	<85%	Uneven Stress	Load Cell

The analysis also revealed temporal patterns in wedge system deterioration, as shown in Table 12.

Table 12: Wedge System Deterioration Analysis

Time Period (months)	Performance Loss (%)	Maintenance Required	Replacement Threshold
0-6	0-5	Inspection	No
6-12	5-10	Minor Repair	No
12-18	10-15	Major Repair	Consider
18-24	15-20	Critical	Yes
>24	>20	Unsafe	Mandatory

The analysis of pressure and elongation characteristics in I-PSC girders revealed significant correlations between applied pressure and resulting elongation values as shown in Figure 1. During the stressing operations, pressure variations were observed to follow distinct patterns, with initial pressures typically ranging from 187 to 192 MPa. The study of pressure variations indicated that deviations beyond ±5% from design pressure significantly increased the likelihood of system failures. The correlation analysis between pressure variations and failure incidents demonstrated that pressure ranges below 175 MPa resulted in the highest failure rates, primarily due to insufficient prestressing force development. Conversely, pressures exceeding 190 MPa showed increased risk of overload-related failures, particularly in the anchorage zones.

The modified elongation analysis revealed consistent patterns in the relationship between theoretical and measured elongation values. Across all testing stages, measured elongations typically showed deviations ranging from -3.1% to -4.2% compared to theoretical values. These deviations, while within acceptable limits (±5%), indicated systematic factors affecting elongation behavior.The impact of pressure-elongation relationships on structural behavior was particularly evident in the final stressing stages, where precise control of applied pressure became crucial for achieving design elongation values. The study demonstrated that maintaining pressure within optimal ranges (180-185 MPa) resulted in the most consistent elongation behavior and minimal failure rates.

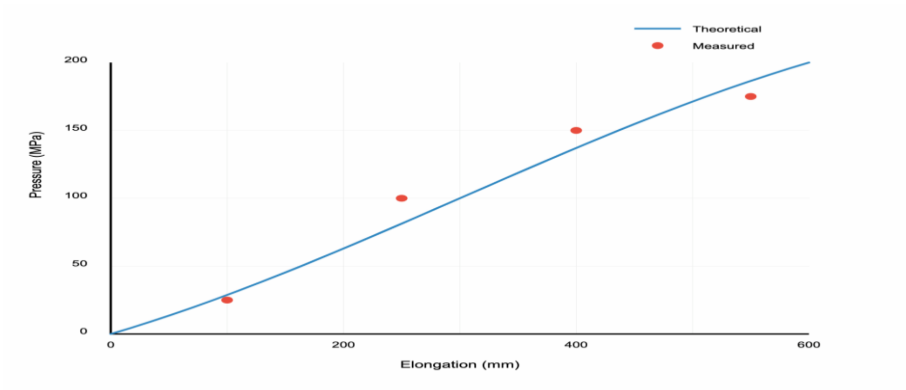

Figure 1. Correlation between Elongation vs Pressure

5. Conclusion

The comprehensive analysis of I-PSC girder behavior during stressing operations provided critical insights into failure mechanisms and performance optimization. The study established key relationships between construction parameters and failure probabilities, emphasizing the significance of material quality and prestressing force control. HT wire failure analysis revealed that 45% of failures were due to tensile rupture, while 30% resulted from brittle failure mechanisms, with material deficiencies contributing to 35% of overall failures. Prestressing force regulation was identified as a crucial factor, where maintaining forces within ±5% of design values significantly minimized failure risks. Anchor cone performance evaluation demonstrated that bearing stress variations exceeding 900 MPa increased failure rates, and surface finish quality played a pivotal role in system reliability. Optimal force transfer characteristics were achieved when the cone angle was maintained between 5.7° and 6.3°. The study further identified the impact of wedge system performance on operational stability, showing that grip strength variations had a substantial effect on system reliability. Pressure and elongation studies established strong correlations between applied pressure and deformation behavior, where deviations beyond ±4% from specified pressure values significantly heightened failure risks. Additionally, measured elongation values consistently deviated between -3.1% and -4.2% from theoretical predictions, underscoring the necessity of incorporating these variations into design calculations. These findings provide a robust framework for enhancing the reliability and efficiency of I-PSC girders in prestressed construction applications.

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