

Structural Performance Assessment of Post-Tensioned PC-U Girders for 25 m and 50 m Industrial Bridge Spans

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Article Information	ABSTRACT
Article History Received : July 18, 2026 Revised : July 31, 2026 Published : October 02, 2026	A 380 m industrial bridge connects the JIPE Industrial Estate to Pulau Segitiga in Gresik, Indonesia. This study evaluates the structural performance of post-tensioned prestressed-concrete U (PC-U) girders for representative 25 m side spans and a 50 m main span using section calculations and three-dimensional SAP2000 analysis. The assessment covers prestressing demand, immediate and time-dependent losses, anchorage-induced principal tensile stress, live-load deflection, and preliminary erection feasibility. Required prestressing forces are 9,278.7 kN and 25,348.7 kN for the 25 m and 50 m girders, respectively. Total prestress losses are 26.1% and 27.6%, below the adopted 28% planning estimate. Maximum principal tensile stresses after anchorage are 2.519 MPa and 2.676 MPa, below allowable values of 2.556 MPa and 2.761 MPa. Live-load deflections are 17.10 mm and 60.35 mm, satisfying the corresponding L/800 limits of 31.25 mm and 62.50 mm. Preliminary lifting checks indicate that the assumed half-girder lifting configurations are feasible within the adopted crane-chart capacities. Both girder configurations satisfy the structural criteria evaluated in this study under the stated assumptions; however, the 50 m girder governs the serviceability and lifting requirements, utilizing 96.6% of the allowable deflection and approximately 90% of the adopted crane-chart capacity. The lifting assessment represents only a preliminary erection-feasibility screening and does not constitute a final lifting or erection plan. Detailed anchorage-zone design, camber verification, construction-stage analysis, temporary stability assessment, field verification, and project-specific erection planning are therefore required before implementation.
Keywords: <i>Structural performance; Post-tensioned PC-U girder; Prestress loss; Multiple span bridge.</i>	

INTRODUCTION

Industrial access bridges require adequate strength, stiffness, durability, and constructability under repetitive heavy-vehicle loading. Post-tensioned prestressed-concrete U (PC-U) girders provide high flexural and torsional stiffness and support prefabricated erection, but longer spans increase prestressing demand, time-dependent losses, anchorage-zone stresses, camber, deflection, and lifting requirements (Wang & Kim, 2022; Bonopera et al., 2020; Jiang et al., 2022, 2023). Span selection should therefore be evaluated through integrated structural and construction performance rather than flexural strength alone.

The investigated 380 m bridge connects the JIPE Industrial Estate to Pulau Segitiga in Gresik, Indonesia. The original scheme used prestressed-concrete I girders, whereas this study assesses representative 25 m side spans and a 50 m main span using post-tensioned PC-U girders. The coastal reclamation area contains very loose sand over very soft to soft clay, which is relevant to later system-level verification, although the present paper focuses on the superstructure (Darmawan et al., 2026; Irmawan et al., 2024). Figure 1 shows the site and bridge alignment.



Figure 1. Satellite view of the bridge location and highlighted connection alignment between the JIPE industrial area and Pulau Segitiga

Previous Indonesian studies have examined span-dependent prestressed-girder design, PC-I versus PC-U prestress losses, and PC-U bridge redesign (Armin et al., 2018; Hidayati et al., 2023; Jepriani et al., 2020). International studies have separately addressed prestress-loss prediction, long-term deformation, modal sensitivity, and anchorage-zone actions (Bonopera et al., 2020; Breccolotti, 2020; Yang et al., 2020, 2020; Yu et al., 2024). Castigliano-based energy analysis has also been proposed as an independent analytical check for prestressed-bridge deflection (Yudoprasetyo et al., 2026). However, relatively few studies compare substantially different PC-U span lengths through one consistent workflow linking section selection, tendon demand, losses, anchorage stress, service deflection, and lifting feasibility.

Accordingly, this study aims to conduct a preliminary structural performance assessment of post-tensioned PC-U girder superstructures for representative 25 m and 50 m spans. The evaluated parameters include prestressing demand, prestress losses, anchorage-zone principal tensile stress, live-load deflection, and preliminary girder-lifting feasibility. The objective is to identify the governing response and remaining design margin of each span under the adopted assumptions, rather than to provide comprehensive optimization or final construction verification.

RESEARCH METHODS

Research Design and Scope

This study adopted a deterministic design-analysis workflow. Existing project drawings, geometric data, material strengths, and site constraints were used to define the 25 m and 50 m representative spans. Preliminary PC-U dimensions were selected from the manufacturer's section data. Manual calculations were then used to determine section properties, prestressing force, tendon and strand requirements, immediate and time-dependent losses, stress states, cracking moment, flexural and shear demand, torsion, and deflection. A three-dimensional SAP2000 model was used to obtain global structural actions and modal characteristics. Each design stage was checked iteratively against the adopted Indonesian bridge, concrete, prestressing-steel, and material provisions, with AASHTO, ACI, and ASTM provisions used as supporting references (American Association of State Highway and Transportation Officials, 2020; American Concrete Institute, 2019; ASTM International, 2018; Badan Standardisasi Nasional, 2016a, 2016b). The analysis was limited to the investigated upper-structure configurations and the lifting feasibility

described in this paper; detailed foundation design, fatigue verification, temporary bracing design, and field load testing were outside the present scope.

General Design Data

The principal geometric, material, and section data are summarized in Table 1. The 25 m girder uses 60 MPa concrete, whereas the 50 m girder uses 70 MPa concrete. The prestressing system was represented by low-relaxation seven-wire strand consistent with ASTM A416/A416M-18. Concrete and reinforcement material requirements were cross-checked against SNI 6880:2016, SNI 2847:2019, and SNI 2052:2024.

Table 1. Geometric, material, and section properties of the PC-U girders used in the 2025 JIPE–Pulau Segitiga bridge assessment.

Parameter	25 m span	50 m span
Bridge location	JIPE–Pulau Segitiga, Gresik	JIPE–Pulau Segitiga, Gresik
Bridge function	Industrial/LNG access bridge	Industrial/LNG access bridge
Bridge width	9,000 mm	9,000 mm
Girder dimensions	1,720 × 1,400 mm	1,900 × 2,300 mm
Concrete compressive strength, f_c	60 MPa	70 MPa
Girder spacing	3,100 mm	3,100 mm
Non-composite area, A	975,259.66 mm ²	1,431,902 mm ²
Non-composite moment of inertia, I	227,930,854,346 mm ⁴	765,406,846,696 mm ⁴
Non-composite Yb	660.909 mm	1,071.234 mm
Non-composite Ya	739.090 mm	1,228.766 mm
Composite area, A	1,523,267.42 mm ²	1,939,259 mm ²
Composite moment of inertia, I	1,438,923,361,221 mm ⁴	1,452,688,789,639 mm ⁴
Composite Yb	971.773 mm	1,425.412 mm
Composite Ya	428.230 mm	1,124.588 mm

Structural Modeling

Three-dimensional analytical models were developed in SAP2000 to represent the bridge deck, PC-U girders, span geometry, and support conditions. The models were used to obtain global internal actions and modal characteristics, while section-level prestress, loss, and stress calculations were independently evaluated by hand. Modal extraction continued until the accumulated participating mass reached at least 90% in each principal horizontal direction, consistent with the adopted Indonesian seismic bridge procedure and supporting dynamic-response literature (Breccolotti, 2020; Direktorat Jenderal Bina Marga, 2021). The 50 m and 25 m models are shown in **Figure 2** and **Error! Reference source not found.**, respectively.

Design Standards and Load Cases

Dead and live actions included self-weight, superimposed dead load, vehicle loading, braking, wind, earthquake, and water-current effects where relevant. Loading and combinations followed SNI 1725:2016, while seismic and modal requirements followed SNI 2833:2016. Prestressed-concrete checks were based on the Bina Marga manuals, SNI 2847:2019, SNI 6880:2016, and AASHTO LRFD as supporting provisions. Strand and reinforcing-steel requirements followed SNI 1154:2016/Amd.1:2019, ASTM A416/A416M-18, and SNI 2052:2024. Because the numerical loading database originated from the project design, the study retained those project actions and did not independently recalibrate every load factor.

Prestressed-Concrete Stress Formulation

The stress evaluation of the post-tensioned PC-U girders was performed using linear-elastic section analysis, assuming that the concrete section remained homogeneous and uncracked at the

evaluated construction and service stages. In the adopted post-tensioning system, the tendons were stressed after the concrete had attained the required compressive strength, and the prestressing force was subsequently transferred to the girder through the anchorage devices. The introduced prestressing force generates an initial compressive stress that counteracts the tensile stresses caused by gravity and traffic loading. The stress calculation therefore considered the combined effects of the direct prestressing force, tendon eccentricity, and external bending moments in accordance with the adopted prestressed-concrete provisions (American Association of State Highway and Transportation Officials, 2020; American Concrete Institute, 2019; Direktorat Jenderal Bina Marga, 2021).

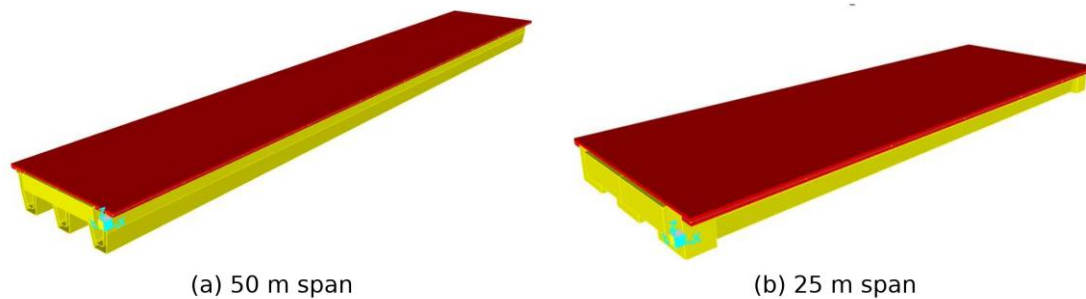


Figure 2. SAP2000 analytical models of (a) the 50 m span and (b) the 25 m span

$$f_{(y)} = -\frac{P}{A} + \frac{P_{ec}}{I} - \frac{M_c}{I} \quad (1)$$

Concrete stresses at the evaluated section were calculated by combining the uniform compressive stress induced by the effective prestressing force, the flexural stress generated by tendon eccentricity, and the stress resulting from external bending moments. The general stress expression is given by Equation (1), where P is the effective prestressing force, A is the gross or transformed sectional area, e is the tendon eccentricity relative to the section centroid, y is the distance from the centroid to the evaluated fiber, I is the corresponding second moment of area, and M is the external bending moment. Compression was taken as negative and tension as positive. The signs of the eccentric-prestress and external-moment terms were assigned according to the evaluated top or bottom fiber.

Prestress-Loss Assessment

The applied prestressing force does not remain fully effective throughout the construction and service life of a post-tensioned girder. Reductions in prestressing force occur during tendon stressing and force transfer and continue to develop as a result of the time-dependent behavior of the concrete and prestressing steel. In this study, the losses were therefore evaluated using a component-based approach that considered elastic shortening, tendon friction, anchorage slip, concrete creep, concrete shrinkage, and steel relaxation. This approach was adopted because the effective prestressing force is influenced by the girder geometry, tendon profile, stressing sequence, material properties, environmental conditions, and elapsed time (Bonopera et al., 2020; Jepriani et al., 2020; Jiang et al., 2022, 2023; Yang et al., 2020; Yu et al., 2024).

$$\Delta_{fp} = \Delta_{fFR} + \Delta_{fAS} + \Delta_{fES} + \Delta_{fCR} + \Delta_{fSH} + \Delta_{fRE} \quad (6)$$

Creep loss was related to sustained concrete stress at tendon level and the elapsed-time creep coefficient. Shrinkage loss was evaluated from the expected free concrete shortening, considering the section volume-to-surface ratio, curing condition, and ambient humidity. Steel relaxation was determined for the adopted low-relaxation strand and initial stress level after accounting for interaction with the other losses. The sum of the six components was used to obtain the effective prestressing force for service-stage stress, cracking, and deflection checks. The

calculated total was also compared with the 28% preliminary value in the Bina Marga practical guide, but this percentage was treated only as a planning benchmark rather than an acceptance criterion.

Allowable Concrete Stress Limits

Concrete stresses were checked against the adopted transfer- and service-stage compressive and tensile limits. The principal tensile stress was calculated from the signed normal stress and shear stress so that anchorage-induced bursting, spalling, or splitting demand could be identified near the girder ends. For a plane-stress state with one dominant normal-stress component, the maximum principal tensile stress was evaluated as follows.

$$\sigma_1 = \frac{\sigma_x}{2} + \sqrt{\left[\left(\frac{\sigma_x}{2}\right)^2 + \tau^2\right]} \quad (7)$$

Flexural and shear resistance were checked using factored demand-to-capacity comparisons, while torsion was assessed against the concrete threshold and the corresponding transverse and longitudinal reinforcement requirements. The cracking moment was used to confirm the applicability of the uncracked service-section assumption. Table 2 summarizes the governing criteria consistently applied to both span alternatives.

Table 2. Adopted structural verification criteria for both PC-U girder spans

Verification item	Adopted criterion	Purpose
Transfer/service stress	Compression and tension within applicable limits	Control excessive compression and concrete cracking
Principal tensile stress	$\sigma_1 \leq f_{t,allow}$	Identify end-zone diagonal tension and anchorage sensitivity
Flexural strength	$M_u \leq \phi M_n$	Confirm ultimate bending resistance
Shear strength	$V_u \leq \phi V_n$	Confirm web and support-region resistance
Live-load deflection	$\delta_{LL} \leq L/800$	Control serviceability and riding performance
Modal participation	Σ modal mass $\geq 90\%$ in X and Y	Represent the global inertial response

Deflection of Girder

Vertical response combined upward prestress camber with downward deflections from girder self-weight, deck weight, superimposed dead load, and live load. The adopted live-load limit was $L/800$. Modal analysis retained sufficient modes to exceed 90% cumulative participating mass in both principal horizontal directions.

RESULTS AND DISCUSSION

U-Girder Dimensions and Section Analysis

The selected dimensions and composite section properties are reported in **Table 1**. The non-composite area of the 50 m section is 1,431,902 mm², which is 46.8% larger than that of the 25 m section, and its non-composite moment of inertia is approximately 3.36 times larger. This increase is consistent with the use of U- or tub-girder geometry to provide greater flexural and torsional stiffness for longer spans (Wang & Kim, 2022). After composite action with the deck, the section areas become 1,523,267.42 mm² and 1,939,259 mm² for the 25 m and 50 m spans, respectively. However, the reported composite moments of inertia differ by only about 1%, indicating that the deck contribution strongly influences the transformed flexural stiffness and that the assumed effective deck width, modular ratio, and neutral-axis locations should be verified during detailed design.

Prestressing Demand and Losses

The required tendon and strand counts were derived from the target prestressing force using the adopted low-relaxation strand area and jacking-stress limit.

The tendon demand and individual immediate and time-dependent loss components are summarized in **Table 3**.

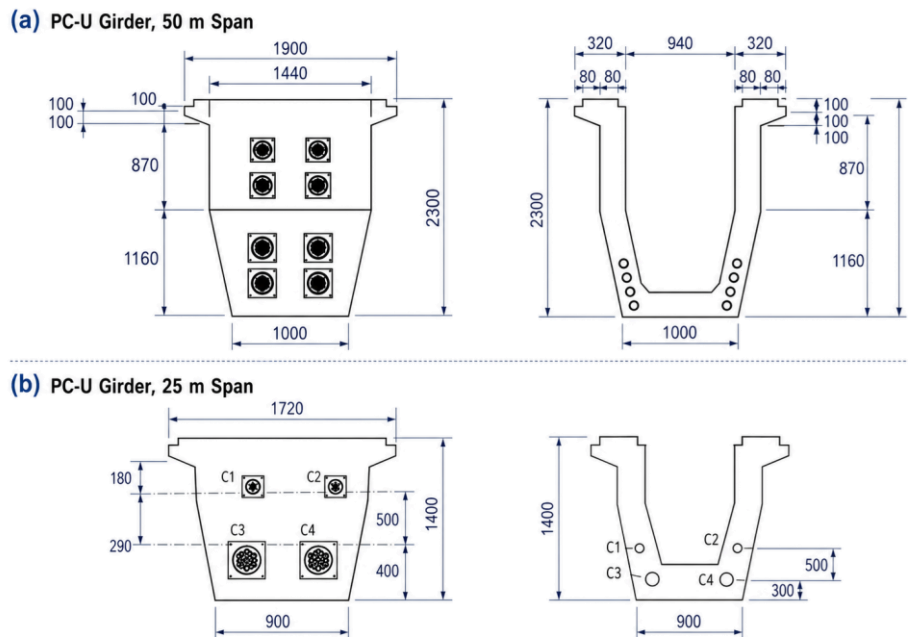


Figure 3. PC-U girder sections and tendon arrangements for (a) the 50 m span and (b) the 25 m span

The 25 m and 50 m girders require 9,278.7 kN and 25,348.7 kN of prestressing force, respectively. The selected arrangements comprise four tendons with 52 strands for the 25 m girder and eight tendons with 150 strands for the 50 m girder. The 2.73-fold increase in force demand reflects the combined effects of span length, self-weight, tendon eccentricity, and service-stress requirements. Tendon distribution and stressing sequence should be confirmed against supplier anchorage capacities and the final construction-stage model.

Total prestress losses are 26.1% for the 25 m girder and 27.6% for the 50 m girder, both below the 28% preliminary Bina Marga estimate (Direktorat Jenderal Bina Marga, 2021). The 50 m value is 1.5 percentage points higher because its larger elastic-shortening and creep components outweigh its slightly lower friction and anchorage-slip losses. This trend is consistent with evidence that effective prestress is controlled by interacting material, geometric, environmental, thermal, and stressing-history effects (Bonopera et al., 2020; Jiang et al., 2022, 2023; Yang et al., 2020; Yu et al., 2024). The 28% value is used only as a preliminary benchmark; final acceptance depends on the resulting effective prestress together with the verified stress and serviceability responses.

Table 3. Prestressing demand and calculated prestress losses for the 25 m and 50 m PC-U girders.

Parameter	25 m span	50 m span
Required prestressing force	9,278.7 kN	25,348.7 kN
Number of tendons	4	8
Number of strands	52	150
Friction loss	5.48%	5.31%
Anchorage-slip loss	5.61%	5.20%
Elastic-shortening loss	1.48%	2.33%
Creep loss	4.15%	5.33%
Shrinkage loss	5.02%	5.02%
Steel-relaxation loss	4.38%	4.38%
Total calculated loss	26.10%	27.60%
Bina Marga planning estimate	28.00%	28.00%

Anchorage-Zone Stress and Serviceability

Principal tensile stresses were evaluated at six stations along each girder before and after including the anchorage-induced stress contribution. The allowable principal tensile stress was determined using the specified 28-day concrete compressive strength, f'_c , of each girder. The 25 m girder was designed with a target strength of 60 MPa, whereas the 50 m girder used 70 MPa concrete. Based on the adopted limit of $0.33\sqrt{f'_c}$, the corresponding allowable principal tensile stresses are 2.556 MPa and 2.761 MPa, respectively. These limits assume that the concrete has attained its specified 28-day strength; therefore, stressing performed at an earlier age must be checked separately using the actual concrete strength at the time of stressing.

The anchorage contribution increases the maximum principal tensile stress from 0.838 MPa to 2.519 MPa for the 25 m girder and from 0.739 MPa to 2.676 MPa for the 50 m girder. These values correspond to utilization ratios of 98.6% and 96.9%, leaving margins of only 0.037 MPa and 0.085 MPa, respectively. Although both values remain below the adopted allowable limits, the small margins indicate high sensitivity to variations in concrete strength, anchorage positioning, reinforcement placement, concrete consolidation, stressing sequence, and construction tolerances. Detailed bursting and spalling reinforcement is therefore required to control cracking and ensure adequate force transfer in the girder.

Table 4. Governing structural-performance and erection checks for the 25 m and 50 m PC-U girders in the 2025 assessment.

Performance indicator	25 m span	50 m span
Maximum principal tensile stress before anchorage	0.838 MPa	0.739 MPa
Maximum principal tensile stress after anchorage	2.519 MPa	2.676 MPa
Allowable principal tensile stress	2.556 MPa	2.761 MPa
Principal-stress utilization	98.6%	96.9%
Chamber	-46,13 mm	-264,21 mm
Live-load deflection	17.10 mm	60.35 mm
Allowable deflection, $L/800$	31.25 mm	62.50 mm
Deflection utilization	54.7%	96.6%
Assessment status	Satisfies adopted criteria	Satisfies adopted criteria

The live-load deflections are 17.10 mm and 60.35 mm for the 25 m and 50 m spans, respectively. These values correspond to 54.7% and 96.6% of the $L/800$ limits, leaving allowances of 14.15 mm and 2.15 mm. The 50 m result is therefore substantially more sensitive to prestress-loss assumptions, composite-section properties, fabrication tolerances, and time-dependent camber than the 25 m result (Birhane et al., 2020; Wicaksana et al., 2024; Zhu et al., 2023). An independent energy-method calculation based on Castigliano's theorem can complement the SAP2000 result and improve traceability of each load contribution (Yudoprasetyo et al., 2026). Field measurement of girder camber before erection and deck casting is also recommended for the 50 m span.

Design Implications, Site Context, and Limitations

The 25 m design is governed more strongly by anchorage-zone tensile stress than by live-load deflection, whereas the 50 m design is simultaneously close to the principal-tension, deflection, and lifting-capacity limits. The JIPE–Pulau Segitiga setting also includes very soft to soft clay and a marine reclamation environment (Irmawan et al., 2024). Although these site conditions are outside the present superstructure model, related Gresik research demonstrates that soil-structure interaction and marine deterioration can change stiffness, lateral demand, and long-term performance of pile-supported infrastructure (Darmawan et al., 2026). Similarly, bearing behavior may alter system periods and seismic-force transfer (Alrasyidi et al., 2026). The present study does not include full construction-stage nonlinear analysis, fatigue, accidental industrial loads, bearing nonlinearity, soil-structure interaction, marine durability, detailed temporary-bracing analysis, or field validation. The reported adequacy is therefore conditional on the stated

assumptions and should be confirmed through independent checking, shop-drawing review, and monitoring of prestress, camber, and erection geometry.

CONCLUSION

This study presents a preliminary structural performance assessment of post-tensioned PC-U girders for representative 25 m and 50 m industrial bridge spans. The required prestressing forces are 9,278.7 kN and 25,348.7 kN, respectively, provided by four tendons with 52 strands for the 25 m girder and eight tendons with 150 strands for the 50 m girder. The calculated total prestress losses are 26.1% and 27.6%, which remain below the adopted 28% preliminary planning estimate.

Anchorage-zone response is critical for both span configurations. The maximum principal tensile stresses reach 2.519 MPa and 2.676 MPa, corresponding to 98.6% and 96.9% of their respective allowable values. Although the calculated stresses remain within the adopted limits, the small residual margins indicate sensitivity to concrete-strength variation, anchorage detailing, reinforcement placement, concrete consolidation, and stressing procedures. Detailed end-zone design, including bursting and spalling reinforcement, is therefore required.

The live-load deflections are 17.10 mm and 60.35 mm for the 25 m and 50 m spans, respectively. The 50 m girder reaches 96.6% of the corresponding $L/800$ limit and consequently governs the serviceability assessment. Its response is particularly sensitive to prestress losses, creep and shrinkage, composite-section properties, fabrication tolerances, and time-dependent camber. Camber and deflection should therefore be verified during fabrication, before erection, and after deck construction.

Overall, both PC-U girder configurations satisfy the structural parameters evaluated in this study under the adopted assumptions. However, the 50 m girder governs because it has the smallest combined margins in anchorage-zone principal tension, live-load deflection, and preliminary lifting capacity. The reported findings should therefore be confirmed through detailed design, construction-stage analysis, independent checking, and field verification before implementation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge PT Berlian Manyar Sejahtera (BMS), as the project owner, for providing the field data, technical information, and supporting documents used in this study. The authors also appreciate the assistance of the project engineering team in facilitating access to the relevant site information required for the structural assessment.

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