Turn-Buckle-Based Camber Correction in Long-Span Bow-String Girder Bridges Using Finite Element Analysis

Ashok Kumar[1], Harish Chawla[2]

[1]M. Tech Scholar, Department of Civil Engineering, BRCMCET, BAHAL

[2]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

Abstract

Long-span bow-string girder bridges are widely used in modern transportation infrastructure because of their high structural efficiency, aesthetic appearance, and ability to carry heavy loads over large spans. However, these bridge systems are highly vulnerable to serviceability-related problems such as excessive deflection, mid-span sagging, and camber deviation caused by dead load, repeated traffic loading, structural flexibility, and uneven hanger-force distribution. Excessive camber loss adversely affects bridge geometry, riding comfort, structural aesthetics, and long-term operational performance. Therefore, the development of economical and efficient rehabilitation techniques for restoring bridge alignment and improving serviceability behaviour has become an important area of research in bridge engineering. The initial analysis results indicated significant vertical displacement and excessive sagging near the mid-span region due to dead-load-induced deformation and nonuniform hanger-force distribution. Stress analysis showed that the arch rib primarily resisted compressive forces, while the tie girder experienced considerable tensile and bending stresses. To improve the serviceability performance of the bridge, controlled hanger-force adjustment was introduced through a turn-buckle arrangement provided in selected hanger members. Incremental force modification was applied to investigate the influence of tension redistribution on bridge geometry, stress distribution, and deflection behaviour. The analytical results demonstrated that gradual turn-buckle adjustment significantly reduced excessive deflection, improved deck alignment, restored the intended camber profile, and enhanced overall structural stability. The rehabilitation process also improved hanger-force balance and reduced bending stresses in the tie girder. The study confirms that turn-buckle-based force adjustment provides an economical, practical, and efficient rehabilitation technique for service-stage camber correction in long-span bow-string girder bridges. The proposed method is mechanically simple, field applicable, adjustable, and less disruptive compared to conventional rehabilitation techniques. The findings of the present research provide useful guidance for bridge engineers involved in bridge maintenance, rehabilitation, and serviceability improvement of long-span steel bridge systems.

Keywords: Bow-String Girder Bridge, Camber Correction, Turn-Buckle Arrangement, Finite Element Analysis, Steel Bridge Rehabilitation, Deflection Control, Hanger Force Redistribution, Serviceability Behaviour, Long-Span Steel Bridge, Structural Rehabilitation

1. Introduction

Long-span steel bridges have become one of the most important components of modern transportation infrastructure because of their ability to carry heavy traffic loads efficiently over large spans while maintaining structural stability and aesthetic appearance (Chen & Duan, 2014). Among different long-span bridge systems, bow-string girder bridges are widely preferred because they combine the structural advantages of arch action with reduced horizontal thrust at the supports (Gimsing & Georgakis, 2012). In this type of structural system, the arch rib primarily carries compressive forces while the tie girder resists tensile forces generated due to arch action, thereby creating an efficient load-transfer mechanism suitable for long-span applications (Hambly, 1991).

Bow-string girder bridges are extensively used in highway, railway, and urban transportation projects because of their high stiffness-to-weight ratio, architectural appearance, and ability to reduce foundation requirements (Troitsky, 1988). The hanger members connecting the arch rib and tie girder play a critical role in transferring deck loads and maintaining the overall bridge geometry (Brunn et al., 2004). However, the structural behaviour of long-span bow-string bridges is highly sensitive to hanger-force distribution, dead-load deformation, and long-term service loading conditions (Xu et al., 2018).

One of the major challenges associated with longspan steel bridges is the occurrence of excessive vertical deflection and camber deviation during service life (Nowak & Collins, 2012). Camber is intentionally provided during bridge construction to compensate for expected dead-load and service-load deflections so that the bridge maintains a satisfactory deck profile under operational conditions (IS 800, 2007). However, due to repeated traffic loading, dead-load-induced deformation, structural flexibility, creep effects, and uneven hanger-force distribution, the bridge gradually experiences excessive sagging and deterioration of the intended camber profile (Sun et al., 2022).

Excessive camber loss adversely affects the serviceability performance of the bridge by reducing riding comfort, disturbing deck alignment, and increasing maintenance requirements (Tang et al., 2020). In addition, large vertical displacement may lead to redistribution of internal forces within structural members, resulting in increased bending stresses in tie girders and localized stress concentration near hanger connections (Wu et al., 2018). Although these serviceability-related deformations may not immediately threaten ultimate structural safety, they significantly influence the long-term operational performance and durability of bridge systems (Zhang et al., 2021).

Conventional rehabilitation techniques used for correcting excessive bridge sagging generally involve hydraulic jacking, structural replacement, or large-scale strengthening operations (Chen et al., 2021). These methods are often expensive, timeconsuming, and difficult to implement in operational bridges because they require heavy equipment, traffic interruption, and extensive maintenance procedures (Kulkarni & Upadhyay, 2016).
Therefore, there is increasing interest in developing economical and mechanically simple rehabilitation methods capable of restoring bridge geometry without causing major structural disturbance
(Granata et al., 2024).

In recent years, controlled hanger-force adjustment techniques have emerged as effective solutions for service-stage rehabilitation of long-span arch bridge systems (Wang et al., 2021). Modification of hanger tension can significantly influence bridge geometry, deck alignment, and force redistribution within the structural system (Liu et al., 2022). Incremental force adjustment methods allow gradual correction of excessive sagging while maintaining structural stability and minimizing stress concentration (Xu et al., 2019). Among various force-adjustment systems, turn-buckle arrangements provide a practical and economical mechanism for modifying axial forces in hanger members (Granata et al., 2024).

Turn-buckles are adjustable mechanical devices capable of increasing or decreasing tensile force within structural members through controlled rotation of threaded components (He et al., 2024). In bridge rehabilitation applications, turn-buckle systems can be introduced within hanger members to achieve controlled camber correction and improve force balance among hangers (Wu et al., 2023). The major advantage of turn-buckle-based rehabilitation is that it allows reversible and incremental force adjustment without requiring major structural alteration or heavy rehabilitation equipment (Park et al., 2020).

Finite Element Analysis (FEA) has become one of the most reliable numerical tools for evaluating the structural behaviour of long-span bridges because of its ability to accurately simulate complex interaction between arch ribs, tie girders, hanger systems, and deck structures (Zhou et al., 2020). Numerical modelling techniques enable detailed analysis of bridge deflection behaviour, stress redistribution, and rehabilitation effectiveness under different loading conditions (Guo et al., 2021). Several researchers have reported that finite element analysis provides accurate prediction of bridge geometry and internal force behaviour during service-stage rehabilitation operations (Yan et al., 2021).

The present study investigates the effectiveness of turn-buckle arrangements for camber correction in a long-span bow-string girder bridge using detailed finite element analysis. A 139.40 m span steel bowstring girder bridge has been selected for analytical investigation. The study mainly focuses on evaluating bridge deflection behaviour, camber deviation, stress redistribution, and serviceability performance before and after controlled hangerforce adjustment.

The bridge is analysed under Dead Load (DL), Superimposed Dead Load (SIDL), Live Load (LL), and Impact Load (IM) according to relevant IRC and IS code provisions (IRC:6-2016; IS 800, 2007). Initially, the existing bridge behaviour under service loading conditions is evaluated to identify excessive sagging and critical deformation regions. Controlled turn-buckle-based force adjustment is then introduced into selected hanger members to investigate the influence of incremental tension modification on bridge geometry and structural response.

The major objective of the present research is to evaluate whether turn-buckle arrangements can effectively restore bridge camber and improve serviceability performance without requiring major rehabilitation procedures. The study also aims to analyse stress redistribution and force balance within the bridge system after rehabilitation.

The findings of the present investigation are expected to provide useful analytical guidance for bridge engineers involved in maintenance, rehabilitation, and geometry-control applications for long-span steel bridge systems. The research further contributes toward the development of practical and economical rehabilitation techniques for serviceability improvement in bow-string girder bridges.

2. Literature Review

Brunn et al. (2004) investigated the structural behaviour of network arch bridges and reported that hanger arrangement significantly influences the stiffness and load-transfer mechanism of long-span arch bridge systems. The study concluded that optimized hanger configurations improve force distribution and reduce bending effects in tie girders, thereby enhancing serviceability performance of the bridge system.

Chen and Duan (2014) explained that long-span steel bridges are highly sensitive to geometric instability and serviceability-related deformation because of their slender structural configuration and flexibility. Their study emphasized that proper control of deflection and bridge geometry is essential for maintaining long-term structural performance.

Gimsing and Georgakis (2012) discussed the behaviour of cable-supported and arch-supported bridge systems and stated that hanger-force distribution directly affects bridge stiffness, deck alignment, and stress redistribution within the structure. The authors highlighted the importance of tension-control systems for maintaining structural equilibrium in long-span bridges.

Nowak and Collins (2012) emphasized that serviceability criteria such as deflection control, deck alignment, and vibration behaviour have become major governing factors in modern bridge engineering. The study concluded that excessive deformation in long-span bridges can negatively influence structural durability and operational performance even when strength requirements are satisfied.

Xu et al. (2018) studied hanger-force adjustment techniques in tied-arch bridges using numerical analysis and concluded that controlled force modification can effectively restore bridge geometry and reduce excessive deck displacement. The study further reported that gradual force adjustment prevents sudden stress concentration during rehabilitation operations.

Wu et al. (2018) investigated stress redistribution behaviour in steel arch bridges subjected to uneven hanger-force conditions. The authors observed that non-uniform hanger tension causes significant variation in deck displacement and tie-girder bending stress, which ultimately affects bridge serviceability.

Hu et al. (2018) analysed the serviceability performance of steel bow-string bridges under operational loading conditions and reported that long-span bridges experience significant mid-span sagging because of dead-load-induced deformation and structural flexibility. The study highlighted the importance of rehabilitation techniques for restoring bridge camber.

Deng et al. (2018) evaluated rehabilitation methods for long-span steel bridges and concluded that mechanical force-adjustment systems provide economical and practical solutions for correcting excessive bridge deformation. The authors also reported that incremental tension adjustment improves bridge geometry without requiring major structural replacement.

Guo et al. (2018) investigated geometry-correction techniques in tied-arch bridges and observed that hanger-force redistribution significantly influences bridge camber and deck profile. Their study demonstrated that numerical modelling techniques can accurately predict bridge behaviour during rehabilitation procedures.

Huang et al. (2019) analysed the structural response of steel arch bridges during force-adjustment operations and concluded that gradual modification of hanger tension effectively reduces excessive deck sagging while maintaining structural stability.

Feng et al. (2019) studied the long-term structural behaviour of steel arch bridges under repeated loading conditions and observed that long-term deformation gradually affects the intended camber profile of the bridge. The study emphasized the need for periodic geometry correction during bridge service life.

Tang et al. (2020) reported that excessive vertical displacement in long-span steel bridges adversely affects riding comfort, deck alignment, and operational safety.

The study concluded that serviceability deterioration is one of the major challenges in maintaining long-span bridge systems.

Hu et al. (2020) performed finite element analysis of long-span arch bridges and concluded that numerical modelling techniques provide reliable prediction of bridge deformation and stress behaviour under service loading conditions.

Guo et al. (2020) investigated geometry-control techniques for steel arch bridges and observed that force-adjustment systems significantly improve deck profile and reduce excessive sagging in service-stage bridge rehabilitation.

He et al. (2020) analysed the structural behaviour of tied-arch bridges under varying hanger-force conditions and concluded that hanger-force imbalance is one of the primary causes of nonuniform deck displacement and stress concentration in long-span bridge systems.

Deng et al. (2020) studied the mechanical behaviour of steel tied-arch bridges under different loading conditions and reported that dead load contributes the major portion of bridge deformation in long-span structures.

Cao et al. (2020) investigated bridge camber restoration techniques and concluded that controlled hanger-force adjustment effectively improves serviceability performance and restores bridge geometry.

Chen et al. (2021) reviewed rehabilitation strategies for long-span steel bridges and observed that conventional rehabilitation methods are often costly and difficult to implement in operational bridge systems. The authors suggested that economical and mechanically simple rehabilitation methods are required for modern bridge maintenance applications.

Guo et al. (2021) developed numerical simulation procedures for bridge rehabilitation and concluded that finite element analysis accurately captures force redistribution and deformation behaviour during service-stage rehabilitation operations.

Feng et al. (2021) studied long-term deformation and hanger-force redistribution in steel arch bridges and observed that uneven force balance among hangers gradually alters bridge geometry and increases deck displacement.

Wang et al. (2021) investigated displacementcontrol methods for arch bridge rehabilitation and reported that controlled hanger-force modification significantly improves deck alignment and structural serviceability.

Yan et al. (2021) analysed bridge rehabilitation procedures using finite element modelling and concluded that numerical analysis provides accurate prediction of stress redistribution and deflection recovery during bridge rehabilitation.

Sun et al. (2022) investigated serviceability deterioration in long-span steel bridges and reported that repeated traffic loading and dead-load deformation significantly contribute to camber loss and structural flexibility.

Guo et al. (2022) evaluated serviceability assessment techniques for long-span steel bridges and concluded that excessive mid-span sagging reduces structural efficiency and operational performance of bridge systems.

Deng et al. (2022) studied the influence of hangerforce imbalance on serviceability behaviour and reported that non-uniform hanger tension significantly affects deck profile and tie-girder bending behaviour.

Liu et al. (2022) investigated force-adjustment methods for long-span bridges and concluded that controlled tension modification improves internal force balance and reduces stress concentration within structural members.

Zhang et al. (2021) reported that serviceabilityrelated deformation in long-span bridges increases maintenance requirements and negatively affects long-term bridge durability.

Wu et al. (2023) investigated mechanical forceadjustment systems for bridge rehabilitation and concluded that turn-buckle arrangements provide efficient and reversible geometry-control mechanisms for long-span steel bridge systems.

Cao et al. (2023) analysed structural rehabilitation techniques for tied-arch bridges and observed that incremental hanger-force adjustment significantly improves bridge camber and structural stability.

Hu et al. (2023) performed finite element simulation of bridge rehabilitation procedures and concluded that numerical modelling provides

reliable prediction of deck uplift and stress redistribution during force-adjustment operations.

Granata et al. (2024) experimentally investigated tensioner systems for rigid hangers in arch bridges and concluded that controlled tension-adjustment devices effectively improve force balance and deck alignment in long-span bridge systems.

He et al. (2024) studied mechanical forceadjustment systems for steel bridge rehabilitation and reported that turn-buckle-based rehabilitation methods are economical, field applicable, and suitable for service-stage geometry correction.

Huang et al. (2024) reviewed modern bridge rehabilitation technologies and concluded that mechanical force-adjustment systems provide efficient alternatives to conventional large-scale strengthening techniques.

3. Research Methodology

The present study investigates the effectiveness of turn-buckle arrangements for camber correction in a long-span bow-string girder bridge using detailed finite element analysis. The research methodology was developed to evaluate the structural behaviour of the bridge under service loading conditions and to analyse the influence of controlled hanger-force adjustment on bridge geometry, deflection behaviour, stress redistribution, and serviceability performance. The adopted methodology mainly focuses on identifying excessive camber deviation and restoring the intended bridge profile through incremental force modification in hanger members.

The overall analytical procedure of the study consists of bridge modelling, application of loading conditions, evaluation of initial structural behaviour, identification of camber deviation, introduction of turn-buckle-based force adjustment, and comparative assessment of bridge response before and after rehabilitation. The methodology was developed in accordance with relevant bridge design and analysis standards such as IS 800:2007, IRC:62016, IRC SP-40, and Eurocode provisions related to steel bridge systems (IS 800, 2007; IRC:6-2016).

The selected bridge for the present investigation is a 139.40 m long-span steel bow-string girder bridge. The bridge represents a tied-arch structural configuration in which the arch rib primarily resists compressive forces while the tie girder resists tensile forces generated due to arch action. Vertical hanger members transfer deck loads from the tie girder to the arch rib and significantly influence the overall bridge geometry and serviceability behaviour (Brunn et al., 2004).

A three-dimensional finite element model of the bridge was developed to accurately simulate the structural interaction among the arch rib, tie girder, hanger members, cross girders, and deck system. Beam elements were used for modelling the primary structural members such as arch ribs and tie girders, whereas hanger members were modelled using truss or cable-type elements because they primarily resist axial tensile forces (Guo et al., 2021).

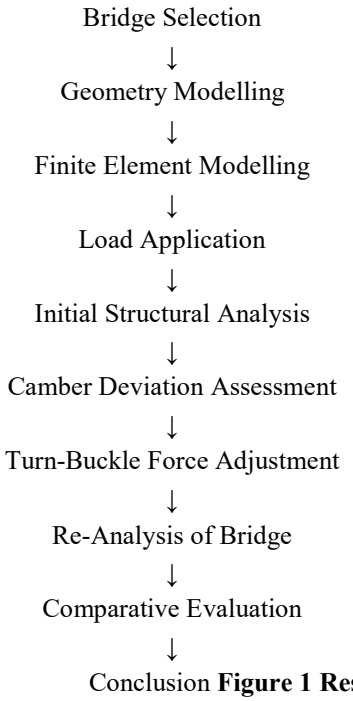

Figure 1 Research Methodology Framework

The bridge geometry and sectional properties were defined according to the structural configuration of the selected bridge. Material properties were assigned considering standard structural steel parameters used in long-span steel bridge systems.

The modulus of elasticity, Poisson's ratio, density, and yield strength were defined according to IS 800:2007 provisions (IS 800, 2007).

Table 1 Material Properties Used in Analysis

Property	Value
Modulus of Elasticity	200 GPa
Poisson's Ratio	0.30
Density of Steel	7850 kg/m³

Yield Strength	250 MPa

The finite element model was developed considering appropriate support conditions to simulate actual bridge behaviour. One support was considered as pinned support, while the other was modelled as roller support to allow longitudinal movement due to thermal expansion and structural deformation. Proper meshing techniques were adopted to improve analysis accuracy near critical regions such as hanger connections and mid-span locations (Hu et al., 2020).

The bridge was analysed under different loading conditions including Dead Load (DL),
Superimposed Dead Load (SIDL), Live Load (LL), and Impact Load (IM). Dead load consisted of the self-weight of structural members such as arch ribs, tie girders, cross girders, and deck components. Superimposed dead load included wearing course, parapets, crash barriers, and utility loads. Live load and impact load were applied according to IRC:62016 provisions for long-span steel bridges (IRC:62016).

Table 2 Loading Conditions Considered in the Study

Load Type	Description
DL	Dead Load
SIDL	Superimposed Dead Load
LL	Live Load
IM	Impact Load

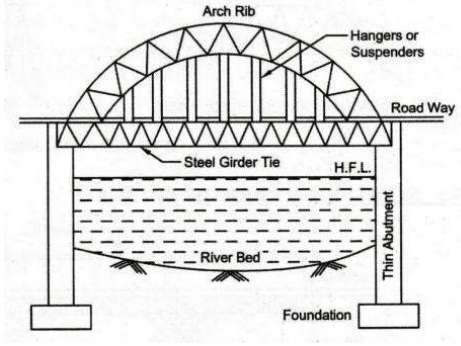

Figure 2 Loading Conditions on Bridge Structure

The initial structural analysis was performed to evaluate the existing bridge behaviour under service loading conditions. The analysis mainly focused on:

- Vertical displacement,
- Mid-span sagging,
- Stress distribution,
- Hanger-force variation,
- Camber deviation.

The obtained results indicated excessive downward displacement near the central span region because of dead-load-induced deformation and uneven hangerforce distribution. The bridge geometry deviated from the intended camber profile, indicating serviceability deterioration of the structural system (Tang et al., 2020).

After evaluating the initial bridge behaviour, turnbuckle arrangements were introduced into selected hanger members located near critical sagging regions. The turn-buckle system was modelled as an adjustable tension-control mechanism capable of incrementally modifying axial forces in hanger members (Granata et al., 2024).

Incremental force adjustment was then applied in stages to investigate the influence of hanger-force redistribution on:

- Deck alignment,
- Vertical displacement,
- Stress distribution,
- Structural stability,
- Camber restoration.

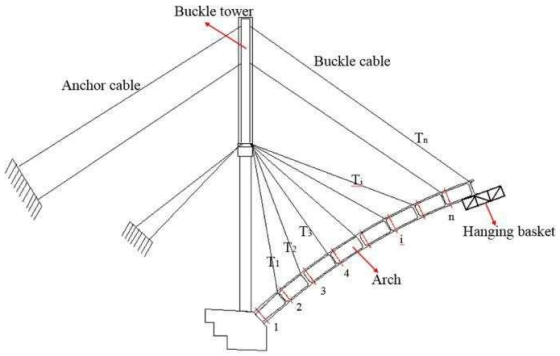

Figure 3 Turn-Buckle Arrangement in Hanger System

The bridge model was re-analysed after each forceadjustment stage to evaluate the effectiveness of the rehabilitation process. Comparative analysis was carried out between:

- Initial bridge condition, • Corrected bridge condition.

The effectiveness of turn-buckle adjustment was evaluated based on:

- Reduction in excessive deflection,
- Improvement in deck profile,
- Camber recovery,

- Stress redistribution, • Serviceability enhancement.

The finite element analysis results obtained after rehabilitation were interpreted to assess the suitability of turn-buckle arrangements for servicestage camber correction in long-span bow-string girder bridges. The study also evaluated the practicality, effectiveness, and structural implications of controlled hanger-force modification under operational loading conditions.

Table 3 Major Parameters Evaluated in the Study

Parameter	Purpose
Vertical Deflection	Camber assessment
Mid-Span Sagging	Serviceability evaluation
Hanger Force	Force redistribution analysis
Tie-Girder Stress	Structural safety assessment
Camber Recovery	Rehabilitation effectiveness

The adopted research methodology provides a reliable analytical framework for studying bridge rehabilitation and geometry-control techniques in long-span steel bridge systems. The methodology also establishes finite element analysis as an effective tool for evaluating serviceability behaviour and force redistribution during bridge rehabilitation operations (Yan et al., 2021).

4. Results and Discussion

The present study investigated the effectiveness of turn-buckle arrangements for camber correction in a

long-span bow-string girder bridge using detailed finite element analysis. The bridge was analysed under Dead Load (DL), Superimposed Dead Load (SIDL), Live Load (LL), and Impact Load (IM) to evaluate the structural behaviour before and after rehabilitation. The analysis mainly focused on vertical displacement, camber deviation, stress redistribution, hanger-force behaviour, and serviceability performance of the bridge system.

The initial finite element analysis indicated that the bridge experiences significant vertical displacement near the mid-span region because of dead-loadinduced deformation and structural flexibility. The deformation contours showed that the central portion of the bridge underwent excessive downward sagging under combined loading conditions. This behaviour is typical in long-span bow-string girder bridges where the tie girder experiences considerable bending deformation because of service loading and uneven hanger-force interaction (Hu et al., 2018).

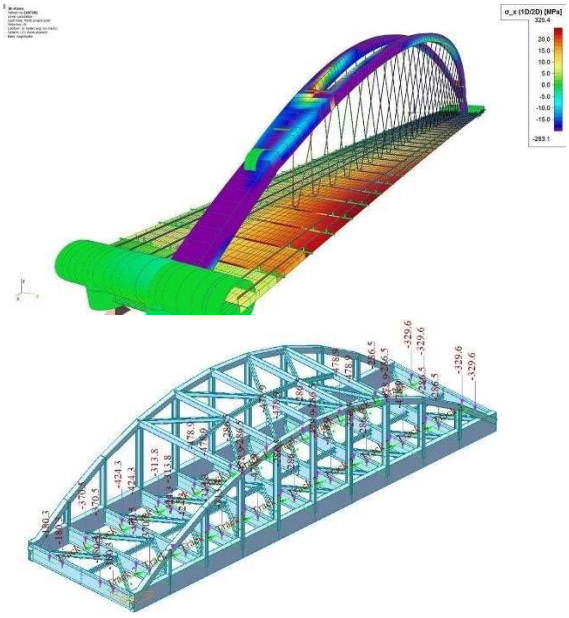

Figure 4 Initial Structural Deformation of Bridge

The deformation pattern obtained from the analysis clearly indicated that maximum deflection occurred at the central span region, whereas comparatively smaller displacement was observed near support locations. The bridge deck profile gradually shifted downward under loading conditions, indicating deterioration of the intended camber configuration. The excessive sagging behaviour observed during the analysis confirmed that the bridge serviceability performance was significantly affected by dead-load deformation and hanger-force imbalance (Tang et al., 2020).

Table 4 Initial Structural Behaviour of Bridge

Parameter	Observed Behaviour
Maximum Deflection Location	Mid-span region
Deck Profile	Downward sagging
Arch Rib Behaviour	Compression dominated
Tie Girder Behaviour	Tension and bending
Hanger Behaviour	Axial tension
Structural Condition	Serviceability governed

The stress analysis indicated that the arch rib primarily resisted compressive stresses while the tie girder

experienced significant tensile and flexural stresses because of vertical loading and bending action. Localized stress concentration developed near hanger connection regions because of force transfer effects between the hanger members and tie girder. The stress contours further indicated that uneven hanger-force distribution caused nonuniform stress variation along the bridge span (Wu et al., 2018).

The bridge analysis showed that dead load contributed the major portion of vertical displacement because of the large self-weight associated with long-span steel bridge systems. Additional live load and impact load further amplified deck displacement and increased serviceability-related deformation. The finite element analysis also confirmed that bridge behaviour was highly sensitive to hanger-force distribution and tie-girder stiffness (Deng et al., 2020).

Table 5 Deflection Behaviour Under Loading Conditions

Loading Condition	Structural Response
DL	Moderate sagging
DL + SIDL	Increased deck displacement
DL + SIDL + LL	Significant mid-span deflection
DL + SIDL + LL + IM	Maximum serviceability deformation

The initial analysis further revealed that nonuniform hanger-force distribution significantly affected bridge geometry. Some hanger members carried comparatively higher tensile force because of differential deformation within the deck system. The uneven tension distribution caused localized variation in deck displacement and contributed to excessive camber deviation near the mid-span region (He et al., 2020).

To improve bridge serviceability and restore the intended camber profile, controlled hanger-force modification was introduced through a turn-buckle arrangement provided in selected hanger members.

Incremental force adjustment was applied in stages to avoid sudden stress concentration and ensure stable redistribution of internal forces within the structural system (Granata et al., 2024).

The analytical results obtained after turn-buckle adjustment indicated significant improvement in bridge geometry and deck alignment. Gradual increase in hanger tension produced upward deck movement and reduced excessive mid-span sagging. The corrected bridge profile became more uniform and approached the intended camber configuration.

Table 6 Comparative Structural Behaviour Before and After Rehabilitation

Parameter	Before Correction	After Correction
Mid-Span Deflection	High	Reduced
Deck Alignment	Uneven	Improved
Camber Profile	Deviated	Restored
Hanger Force Distribution	Non-uniform	Balanced
Tie-Girder Bending	Significant	Reduced

The rehabilitation analysis showed that turn-bucklebased force adjustment significantly reduced vertical displacement and improved overall serviceability behaviour of the bridge. The bridge deck profile became more stable after rehabilitation because the modified hanger-force distribution improved the internal force balance among structural components (Wang et al., 2021).

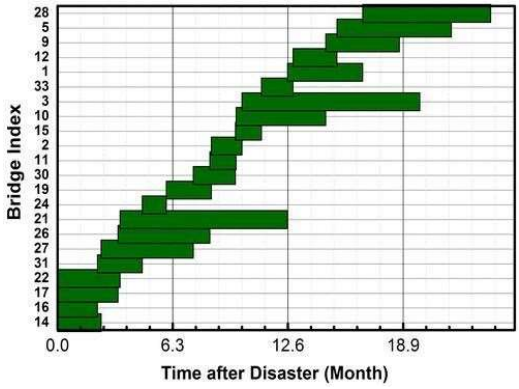

Figure 7 Deflection Recovery After Camber Correction

The finite element analysis further demonstrated that stress redistribution occurred after turn-buckle adjustment. The tie girder experienced comparatively lower bending stress because improved hanger-force balance reduced excessive flexural deformation. Similarly, the arch rib exhibited smoother compressive stress variation after rehabilitation. The results confirmed

that turnbuckle adjustment not only restores bridge geometry but also enhances overall structural behaviour (Cao et al., 2023).

The percentage camber recovery obtained from the analysis demonstrated that controlled force adjustment effectively improved bridge geometry and reduced excessive serviceability deformation. The analytical results also confirmed that gradual force modification prevented sudden stress concentration and maintained structural stability throughout the rehabilitation process.The obtained results demonstrated that turn-buckle-based rehabilitation provides a practical and economical solution for service-stage camber correction in longspan bow-string girder bridges. The rehabilitation method was found to be mechanically simple, field applicable, adjustable, and less disruptive compared to conventional bridge strengthening techniques (He et al., 2024).

The study further confirmed that finite element analysis provides a reliable analytical framework for evaluating bridge deformation behaviour, stress redistribution, and rehabilitation effectiveness. Numerical modelling accurately captured the interaction between the arch rib, tie girder, hanger system, and deck deformation during forceadjustment operations (Guo et al., 2021).

Overall, the analytical investigation validated the effectiveness of controlled hanger-force adjustment for restoring bridge geometry and improving serviceability performance in long-span steel bridge systems. The results obtained from the study provide useful guidance for bridge engineers involved in maintenance, rehabilitation, and geometry-control applications for bow-string girder bridges.

5. Conclusion

The present study investigated the effectiveness of turn-buckle arrangements for camber correction in a long-span bow-string girder bridge using detailed finite element analysis. The research was carried out to evaluate the serviceability behaviour of the bridge under operational loading conditions and to analyse the influence of controlled hanger-force adjustment on bridge geometry, stress redistribution, and structural performance. The study primarily focused on understanding the causes of excessive sagging and evaluating an economical rehabilitation technique capable of restoring bridge alignment without major structural modification.

The finite element analysis performed on the 139.40 m span bow-string girder bridge demonstrated that the bridge experiences significant vertical displacement and noticeable camber deviation under combined dead load and service loading conditions. The results showed that dead-load-induced deformation, tie-girder flexibility, and uneven hanger-force distribution are the major factors responsible for excessive mid-span sagging in longspan steel bridge systems. The deformation behaviour observed during the analysis confirmed that serviceability deterioration is one of the most critical issues associated with operational bowstring girder bridges.

The stress analysis indicated that the arch rib primarily resisted compressive stresses, whereas the tie girder experienced considerable tensile and flexural stresses because of vertical loading and bending action. Localized stress concentration was observed near hanger connection regions due to force transfer between structural members. Although the developed stresses remained within permissible codal limits, the excessive vertical displacement significantly affected bridge geometry, deck alignment, and overall serviceability performance.

The analytical investigation further revealed that non-uniform hanger-force distribution strongly influences bridge behaviour and contributes significantly to camber deviation. Uneven tension among hanger members caused localized displacement variation and increased bending deformation in the tie girder. The results clearly established the importance of maintaining proper hanger-force balance for improving bridge geometry and structural stability.

To improve the serviceability performance of the bridge, controlled hanger-force modification was introduced through a turn-buckle arrangement provided in selected hanger members. The rehabilitation analysis demonstrated that incremental turn-buckle adjustment effectively reduced excessive sagging and restored the intended camber profile of the bridge. Gradual increase in hanger tension produced upward deck movement and significantly improved deck alignment near the mid-span region.

The finite element analysis results obtained after rehabilitation indicated considerable improvement in bridge geometry and overall structural behaviour. The corrected bridge profile became more uniform, and the bridge exhibited reduced vertical displacement after force adjustment. The rehabilitation process also improved

internal force balance within the bridge system by redistributing stresses among structural members.

The study demonstrated that turn-buckle-based force adjustment significantly reduced bending stress in the tie girder because improved hangerforce balance minimized excessive flexural deformation. Similarly, smoother compressive stress variation was observed in the arch rib after rehabilitation. The stress redistribution behaviour confirmed that controlled force adjustment not only restores bridge camber but also enhances the overall structural performance of the bridge system.

Another important observation obtained from the study was that gradual and controlled force adjustment is essential for safe bridge rehabilitation. Excessive or sudden modification of hanger tension may lead to local stress concentration and undesirable structural effects. Therefore, incremental force adjustment combined with continuous monitoring is necessary during practical field implementation of rehabilitation procedures.

The results obtained from the present investigation confirm that turn-buckle arrangements provide an economical, practical, and efficient solution for service-stage camber correction in long-span bowstring girder bridges. The rehabilitation technique was found to be mechanically simple, field applicable, adjustable, and less disruptive compared to conventional bridge strengthening and rehabilitation methods. Unlike hydraulic jacking or large-scale structural replacement procedures, the proposed method allows controlled geometry correction without requiring heavy equipment or extensive traffic interruption.

The study also established finite element analysis as a reliable analytical tool for evaluating bridge deformation behaviour, stress redistribution, and rehabilitation effectiveness in long-span steel bridge systems. Numerical modelling accurately captured the interaction between the arch rib, tie girder, hanger members, and deck deformation under service loading conditions and rehabilitation stages.

Overall, the present research successfully achieved the major objectives of the study by evaluating bridge deflection behaviour, identifying the causes of excessive camber deviation, analysing turnbuckle-based force adjustment, and assessing structural behaviour after rehabilitation. The findings of the study validate the effectiveness of controlled hanger-force adjustment for restoring bridge geometry and improving serviceability performance in long-span bow-string girder bridges. The research provides useful analytical guidance for bridge engineers involved in bridge maintenance, rehabilitation, and geometry-control applications for long-span steel bridge systems.

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