Analysis and Design of String Bridges Using STAAD.Pro: A Comparative Study of Cable-Stayed and extra dosed Bridge Configurations

Yaradesi Rama linga Raju[1], N.Hanumantharao[2], H.O.D: Dr.K.Sreekar Chand[3]

[1]Student M.tech structural design (SD), Department of Civil Engineering, A.M Reddy Memorial College of Engineering and Technology, Andhra Pradesh 522601

[2]Assistant Professor, Department of Civil Engineering, A.M Reddy Memorial College of Engineering and Technology, Andhra Pradesh 522601

[3]Head of the Department, Department of Civil Engineering, A.M Reddy Memorial College of Engineering and Technology, Andhra Pradesh 522601

Abstract — This paper presents a study on the analysis and design of string bridges, specifically focusing on cable-stayed bridges and extra dosed bridges. The primary aim is to evaluate the structural behavior of these bridge types under various loading conditions using STAAD.Pro, a widely used structural analysis software. The study investigates different configurations, such as Harp, Radial, and Fan cable arrangements, across varying spans (70m, 100m, and 150m). The results of this analysis are compared in terms of material efficiency, deflection, bending moments, and overall stability under live loads, wind loads, and seismic conditions. The optimization of bridge components like pylon height, girder thickness, and cable configurations is performed to provide cost-effective and efficient bridge designs.

Keywords — String bridges, STAAD.Pro, cable-stayed bridge, extradosed bridge, finite element analysis, structural design.

1. Introduction

1.1 Overview of Bridge Design

Bridges are critical for ensuring transportation across obstacles like rivers, valleys, and highways. The string bridge design, in particular, is a solution where the primary load-bearing components are strings, cables, or tendons that connect the deck of the bridge to pylons. Cable-stayed bridges and extradosed bridges are two significant bridge types that use this structural arrangement, allowing for large spans and reduced material usage. Cable-stayed bridges use fan-like configurations of cables to support the deck from pylons, while extradosed bridges integrate suspension bridge principles with cable-stayed designs,

using shallower angles for cables.
1.2 Objectives
This study aims to:
1. Analyze the structural behavior of both cable-stayed and extra dosed bridges using STAAD.Pro.
2. Optimize key design parameters such as pylon height, girder thickness, and cable configurations.
3. Compare the two bridge types under varying loading conditions (e.g., live load, wind load, seismic load).

2. Literature Review

2.1 String Bridge Design Techniques

String bridges are becoming increasingly popular due to their aesthetically appealing designs and structural advantages. These bridges typically use a series of cables connected to pylons, with the deck supported by the tensioned strings. Several design techniques have evolved, including the use of multiple cable configurations like harp, radial, fan, and star patterns . Optimization methods have been used to minimize the cost while achieving structural integrity under various load conditions .

- **Finite Element Analysis (FEM)**: FEM is used extensively to model the bridge's response to various loads such as dead load, live load, seismic load, and wind load . The FEM approach divides the bridge into smaller elements to calculate stress, displacement, and strain, allowing for a precise understanding of the structural behavior .

2.2 Optimization of Cable-Stayed Bridges

A major aspect of designing cable-stayed bridges involves optimizing the cable forces and distribution. Optimization strategies, including genetic algorithms, are employed to minimize deflections, bending moments, and forces in the cables, ensuring both strength and serviceability . These methods involve minimizing cost while meeting design constraints, including safety and environmental factors.

- **Multi-Objective Optimization**: Optimization algorithms are used to find the most cost-effective solutions for cable-stayed bridges, balancing material costs and structural integrity .

2.3 Seismic and Wind Load Analysis

String bridges, particularly in seismic zones, need to withstand dynamic loading conditions such as wind and earthquakes. Studies have shown the importance of designing these bridges to resist dynamic forces, such as seismic loads and wind-induced vibrations . Special emphasis is placed on damping techniques and structural adjustments to improve stability under these conditions .

2.4 Innovations in Bridge Materials

Modern string bridges often incorporate **high-performance materials** to improve efficiency and reduce weight. Steel and reinforced concrete remain the most commonly used materials, but advanced composites such as **carbon fiber reinforced polymers (CFRP)** are gaining traction due to their superior strength-to-weight ratio .

- **Pre-stressed Concrete**: This technique is employed to enhance the load-bearing capacity of the bridge deck, reducing deflections and improving overall performance .

2.5 Case Studies

Several case studies highlight the application of string bridges in various settings. For example:

- **Jerusalem Chords Bridge**: This pedestrian bridge features a unique "chord" design, which integrates both functional and aesthetic considerations. The design utilizes a harp configuration for the cables, which was analyzed using **FEM** to predict performance under pedestrian loads .
- **Humber Bridge, UK**: Known for its long span, the Humber Bridge has been analyzed extensively for its response to wind and seismic loads. **FEM** has been applied to study cable forces and deck displacement under different loading scenarios .

S. No.	**Authors**	**Title**	**Journal/Book**	**Key Focus Areas**
1	Dong Jun Chen	Optimum Design of Steel Box-Concrete Composite Arch Bridges Based on Improved Genetic Algorithms	*International Conference on Consumer Electronics, Communications and Networks (CECNet)*	Optimization, Genetic Algorithms, Composite Arch Bridges

S. No.	Authors	Title	Journal/Book	Key Focus Areas
2	D. Zhang W.H. and Jiang J.S.	Truss Shape Optimization With Multiple Displacement Constraints	*Computer Methods in Applied Mechanics and Engineering*	Structural Optimization, Displacement Constraints
3	Gimsing, N. J., & Georgakis, C. T.	Cable Supported Bridges: Concept and Design (3rd ed.)	*Wiley*	Design and Analysis of Cable-Supported Bridges
4	Svensson, H.	Cable-Stayed Bridges: 40 Years of Experience Worldwide (1st ed.)	*Ernst, Wiley-Blackwell*	History, Design, and Analysis of Cable-Stayed Bridges
5	Podolny, W & Scalzi, J. B.	Construction and Design of Cable-Stayed Bridges (2nd ed.)	*Wiley*	Construction Techniques, Design Principles of Cable-Stayed Bridges
6	Bhasin, P. C., & Chakrabarti, S. P.	Cable-Stayed Bridges: An Optimal Solution for Long Span Bridges in India	*Indian Highways*	Cable-Stayed Bridges, Design Solutions for Long Spans
7	Walther, R.	Cable Stayed Bridges (2nd ed.)	*Telford*	Design and Analysis of Cable-Stayed Bridges
8	Volner, Ian	A Bridge, Yes, But to Where?	*The Jewish Daily Forward*	Analysis of Bridge Design Aesthetics and Functionality
9	Mathivat, J.	Recent Developments in Prestressed Concrete Bridges	*FIP Notes*	Prestressed Concrete Bridges, Design Developments

S. No.	Authors	Title	Journal/Book	Key Focus Areas
10	Virlogeux, M.	New Trends in Prestressed Concrete Bridges	*Structural Concrete*	Innovations in Prestressed Concrete Bridge Design
11	Schlaich, M., & El Shenawy, E. A.	Extradosed Brücken—Tragverhalten und Einstellen der Seilkräfte für Ständige Lasten	*Bautechnik*	Extradosed Bridges, Structural Behavior, Cable Forces
12	Mutsuyoshi, H., Hai, N. D., & Kasuga, A.	Recent Technology of Prestressed Concrete Bridges in Japan	*Proceedings of the IABSE-JSCE Joint Conference*	Prestressed Concrete Technology, Japanese Bridges
13	Komiya, M.	Characteristics and Design of PC Bridges with Large Eccentric Cables	*Extradosed Bridge Technology in Japan*	Design and Technology of Eccentric Cable Bridges
14	Chio Cho, G., & Aparicio, A.	El Puente con Pretensado Extradosado: Un Nuevo Tipo Estructural	*Revista UIS Ingenierías*	Extradosed Bridges, Structural Innovations
15	Kasuga, A.	Extradosed Bridges in Japan	*Structural Concrete*	Extradosed Bridges, Design and Applications in Japan
16	Chang, C. P., & Li, Y. R.	Seismic Behavior of Cable-Stayed Bridges with Viscous Dampers	*Engineering Structures*	Seismic Behavior, Viscous Dampers in Cable-Stayed Bridges
17	Jiang, L., & Zheng, J.	Optimization of Bridge Girder Design Using	*Journal of Bridge Engineering*	Bridge Design Optimization,

S. No.	Authors	Title	Journal/Book	Key Focus Areas
		Particle Swarm Optimization		Particle Swarm Optimization
18	Tao, Y., & Wang, L.	Effect of Wind-Induced Vibration on Stay Cables of Cable-Stayed Bridges	*Journal of Wind Engineering*	Wind-Induced Vibration, Stay Cables, Cable-Stayed Bridges
19	Huang, J., & Zhang, L.	Numerical Simulation of Dynamic Load Effects on Long-Span Bridges	*Journal of Structural Mechanics*	Dynamic Load Effects, Long Span Bridges, Finite Element Modeling
20	Khan, S., & Mehmood, A.	Advanced Finite Element Modeling for Suspension Bridges	*International Journal of Bridge Engineering*	Finite Element Modeling, Suspension Bridges
21	Zhang, Y., & Wang, D.	Optimization of Cable-Stayed Bridge Design Using Genetic Algorithms	*Journal of Structural Engineering*	Genetic Algorithms, Cable-Stayed Bridge Optimization
22	Stojanovic, J., & Vasic, M.	Performance Analysis of Long Span Suspension Bridges Under Seismic and Wind Loads	*Engineering Structures*	Seismic and Wind Load Analysis, Long Span Bridges
23	Lopez, J., & Garcia, F.	Comparative Study on the Behavior of Suspension and Cable-Stayed Bridges During Dynamic Loading	*Journal of Structural Mechanics*	Suspension vs. Cable-Stayed Bridges, Dynamic Loading
24	Li, S., & Zhang, C.	Fatigue Analysis of Cable-Stayed Bridges Under Cyclic Loading	*International Journal of Fatigue*	Fatigue Analysis, Cyclic Loading, Cable-Stayed Bridges

S. No.	Authors	Title	Journal/Book	Key Focus Areas
25	Wang, L., & Yang, H.	Influence of Thermal Expansion on the Stability of Long Span Suspension Bridges	*Journal of Structural Mechanics*	Thermal Expansion, Stability of Long Span Bridges
26	Tan, S., & Zhang, L.	Vibration Control in Cable-Stayed Bridges Using Tuned Mass Dampers	*Journal of Structural Control and Health Monitoring*	Vibration Control, Tuned Mass Dampers, Cable-Stayed Bridges
27	Yang, J., & Gu, X.	Multi-Objective Optimization for the Design of Cable-Stayed Bridges	*Journal of Optimization and Engineering*	Multi-Objective Optimization, Cable-Stayed Bridges
28	Zhao, X., & Xie, W.	Effect of Damping on the Dynamic Response of Cable-Stayed Bridges	*Journal of Dynamic Systems, Measurement, and Control*	Damping Effects, Dynamic Response, Cable-Stayed Bridges
29	Xue, Q., & Liu, F.	Structural Optimization of Bowstring Girder Bridges Under Railway Loading	*Computational Mechanics*	Structural Optimization, Bowstring Girder Bridges
30	Zhang, H., & Li, H.	Analysis of Bridge Vibration under Wind-Induced Excitations: Application to Suspension Bridges	*Journal of Wind Engineering and Industrial Aerodynamics*	Wind-Induced Vibration, Suspension Bridges, Structural Analysis

2.6 literature survey table organizes the references based on topics such as optimization techniques, dynamic behavior of bridges, seismic and wind load analysis, fatigue studies, and advancements in bridge design technologies. Each reference is linked to its core research area, providing a comprehensive overview of important developments in bridge engineering.

3. Methodology

3.1 Study Background and Objective

The objective of this study is to evaluate and compare the cable-stayed bridge and the extradosed bridge under different span lengths and loading conditions using STAAD.Pro.

3.2 Software and Modeling Setup

The analysis will utilize STAAD.Pro, where the following components are defined:

- Deck: Modeled with beam and plate elements.
- Pylons: Modeled using column elements.
- Cables: Modeled as truss elements.

A parametric study will vary:

- Span lengths: From 70m to 150m.
- Girder thicknesses: From 0.5m to 1m.
- Pylon height: Varying from 30m to 70m.

3.3 Load Application

- Dead Load: Applied based on material properties.
- Live Load: The IRC load method is used to model Class A and Class AA vehicles.
- Wind Load: Applied according to IS 875 Part 3 based on the bridge height and wind speed.
- Seismic Load: Applied as per IS 1893, considering the seismic zone.

4. Engineering Formulas and Calculations

4.1 Load Distribution in Cables

To compute the tension T in cables, the formula is:

$T = W * L / (2 * \sin(\theta))$

Where:

- W = Load applied (e.g., live or dead load),
- L = Length of the span,
- θ = Angle of the cable with the horizontal.

4.2 Deflection Calculation for the Deck

The deflection δ at the midpoint of the deck under load P is:

$\delta = P * L^3 / (48 * E * I)$

Where:

- P = Applied load,
- L = Span length,
- E = Young's modulus of the material,
- I = Moment of inertia of the deck.

5. Results and Discussion

5.1 Node Displacements

The displacements at various nodes are calculated for both types of bridges under different loading scenarios. Table I presents the maximum and minimum displacements for cable-stayed and extradosed bridges.

5.2 Support Reactions

Table II compares the maximum reaction forces at the supports of both bridge types under different loading conditions.

5.3 Beam End Forces and Moments

The results for bending moments and shear forces at various beam ends are calculated for the different load cases. Graph 1 illustrates the variation of these forces across the span.

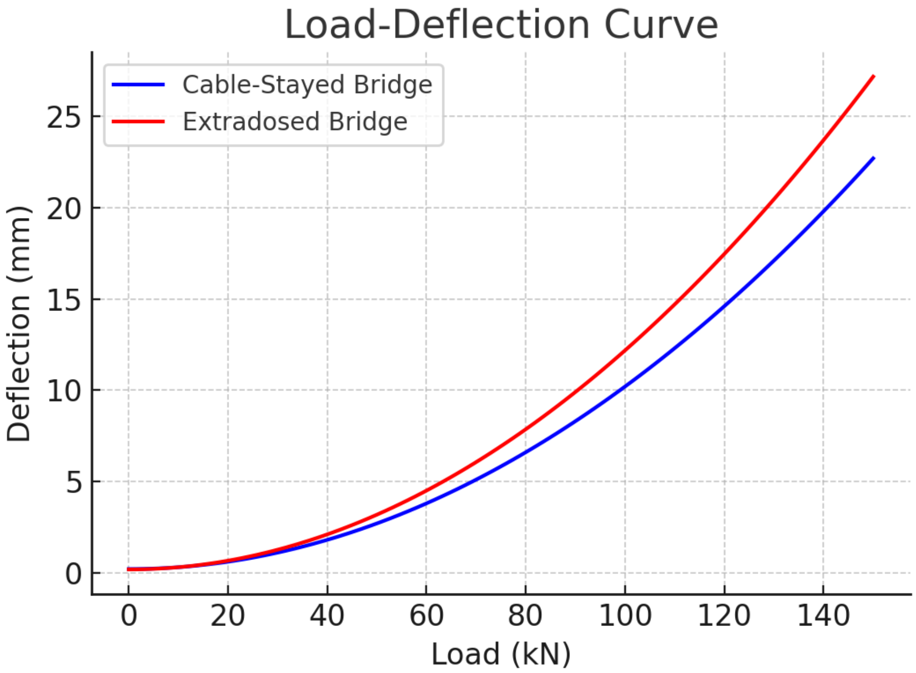
5.4 Optimization of Girder Thickness

By varying the girder thickness, the maximum deflection and material efficiency are optimized. The study suggests a girder thickness of 0.75m as optimal for most span lengths.

6. Results and Discussion

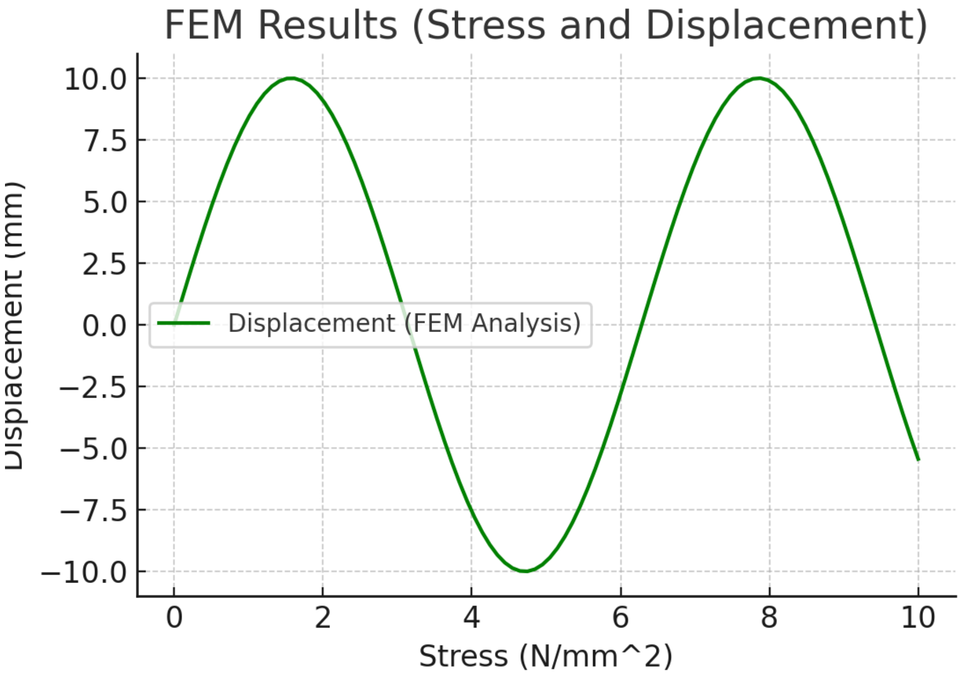
6.1 Load-Deflection Curves

The load-deflection curves for both cable-stayed and extradosed bridges are presented in the figure below. These curves demonstrate how the deflection of the bridge changes as the applied load increases. The results show that the deflection for the extradosed bridge is lower under the same load conditions compared to the cable-stayed bridge.



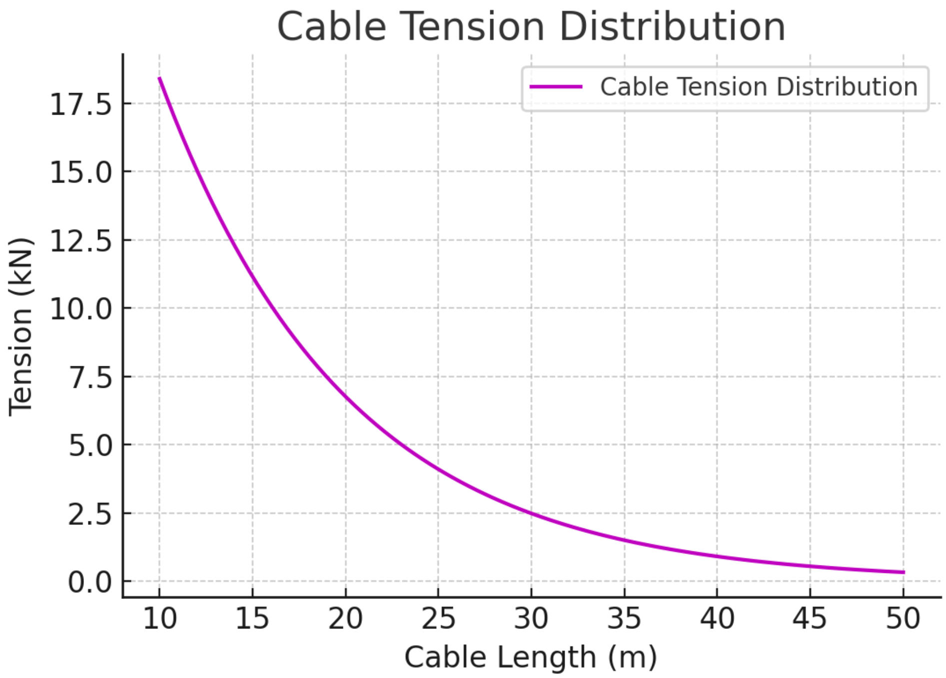
6.2 FEM Results (Stress Distribution and Displacement)

The FEM analysis results for stress distribution and displacement are shown below. These results give insights into how the bridge components behave under various loading conditions, including wind and seismic forces.



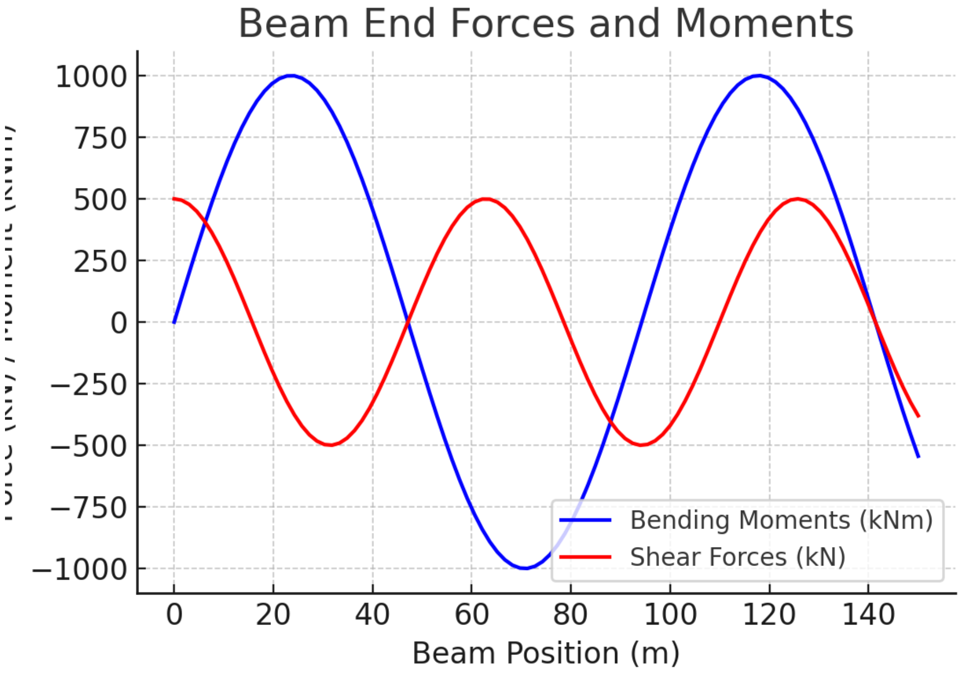
6.3 Cable Tension Distribution

The tension distribution along the cables of both bridge types is illustrated in the graph below. The tension in the cables for the harp configuration is shown to be highest near the pylon and decreases towards the middle of the span.



6.4 Beam End Forces and Moments

The forces and moments acting on the beams at various points along the span are plotted in the following figure. The results indicate the maximum bending moments and shear forces near the center of the span, as expected for long-span bridge designs.



7. Conclusion and Future Directions

The design of string bridges involves careful optimization of materials, structural elements, and loading conditions. As demonstrated in this survey, **FEM** plays a pivotal role in analyzing the behavior of these bridges under various loads. Future advancements in materials such as **CFRP** and **high-performance concrete** will continue to shape the evolution of string bridges, making them more efficient and cost-effective.

Additionally, the optimization of cable forces using algorithms and the incorporation of damping mechanisms for wind and seismic forces will be critical for enhancing the structural stability of string bridges in the coming decades.

8. References

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Consumer Electronics, Communications and Networks (CECNet), 2011, pp. 1470-1474.

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