DESIGN AND ANALYSIS OF CABLE STAYED BRIDGES

REPORT OF MINI PROJECT - I

Submitted in partial fulfilment of the requirements for the degree of

BACHELOR OF TECHNOLOGY

In

CIVIL ENGINEERING

By

P Geetha (231CV238)

Srushti D S (231CV254)

Keerthipraba (231CV225)

Bhumika Meena (231CV213)

Under the guidance of

Dr. Prashanth M H

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE – 575025

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DECLARATION

We hereby declare that the Report of the MINI Project- 1 work entitled "***Design and Analysis of Cable Stayed Bridge***" which is being submitted to the National Institute of Technology Karnataka, Surathkal in the award of the Degree of Bachelor of Technology in the department of Civil Engineering, is a bonafide report of the work carried out by us. The material contained in this Project Work Report has not been submitted to any University or Institution for the award of any degree.

BY :

P Geetha (231CV238)

Srushti D S (231CV254)

Keerthipraba (231CV225)

Bhumika Meena (231CV213)

Place : NITK Surathkal

Date : 25-11-2025

CERTIFICATE

This is to certify that this report entitled **“Design and Analysis of Cable Stayed Bridges”** being submitted by **P Geetha (231CV238) , Srushti D S (231CV254) , Keerthipraba (231CV225) , Bhumika Meena (231CV213)** is accepted as the record of work carried out by them as the part of a Mini Project-I in partial fulfilment of the requirements for the award of the degree of the **Bachelor of Technology** in **Civil Engineering** of the **Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal.**

Signature of guide

Signature of HOD
Civil Engineering Department

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P Geetha (231CV238)

Srushti D S (231CV254)

Keerthipraba (231CV225)

Bhumika Meena (231CV213)

ABSTRACT

The design and analysis of bridges are critical components of civil engineering that ensure safe, efficient, and durable transportation infrastructure. This report examines the fundamental principles, methodologies, and modern tools used in bridge engineering, covering both conceptual design and detailed structural analysis. It explores key factors influencing bridge performance—including material selection, loading conditions, structural systems, and environmental considerations—as well as the application of analytical methods such as finite element modeling and load-resistance factor design. The report also highlights contemporary challenges, including sustainability, resilience to natural hazards, and the integration of advanced technologies like sensor-based monitoring and computational optimization. Through a comprehensive review of design strategies and analytical approaches, this work aims to provide a cohesive understanding of how bridges are conceived, evaluated, and refined to meet the evolving demands of society.

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1. INTRODUCTION

1.1 Earth's Interior

Earth's interior is made up of several layers, each with unique physical and chemical properties. Although we cannot travel deep inside the planet, scientists study its interior using indirect evidence such as seismic waves, volcanic materials, and Earth's magnetic field. These studies reveal that Earth is structured in **three main layers**—the **crust**, **mantle**, and **core**—each playing a crucial role in shaping the planet's behaviour.

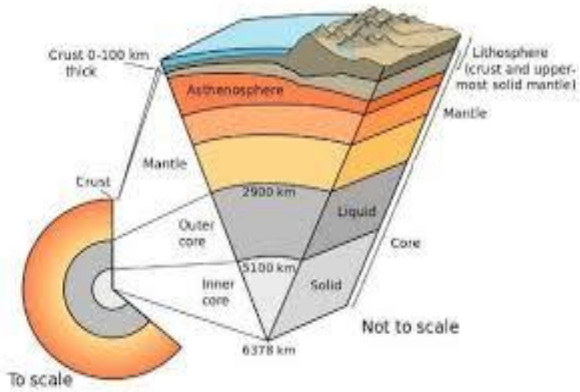


Fig.1 Earth's interior

1. Crust

The crust is Earth's outermost and thinnest layer. It is solid and divided into large pieces called tectonic plates. There are two types:

- **Continental crust** (thicker but less dense)
- **Oceanic crust** (thinner but denser)

2. Mantle

Beneath the crust lies the mantle, a thick layer made of semi-solid rock. It is divided into the upper and lower mantle. Convection currents in the mantle drive the movement of tectonic plates and cause earthquakes, volcanic activity, and mountain building.

3. Core

The core is Earth's innermost layer and consists of:

- A **liquid outer core**, responsible for generating Earth's magnetic field.
- A **solid inner core**, made mostly of iron and nickel.

1.2 Origin of Earthquakes

Earthquakes are caused by the sudden release of energy within the Earth's crust. This energy release produces seismic waves, which shake the ground. Most earthquakes occur due to the movement of tectonic plates—large pieces of Earth's crust that are constantly shifting over the mantle.

1. Tectonic Plate Movements (Most Common Cause)

The Earth's lithosphere is broken into plates that move slowly. When these plates interact, stress builds up along their boundaries. When the stress becomes too great, the rocks break or slip suddenly, causing an earthquake.

Types of plate boundaries that produce earthquakes:

- **Transform boundaries** – plates slide past each other (e.g., San Andreas Fault).
- **Convergent boundaries** – plates collide, often causing powerful quakes.
- **Divergent boundaries** – plates pull apart, causing weaker but frequent quakes.

1.3 Bridges

Bridges are essential structures that help people and goods move easily from one place to another by **crossing obstacles** such as rivers, valleys, lakes, railways, and busy roads. Without bridges, travel would be longer, more difficult, and sometimes even impossible.

Why Do We Need Bridges?

Connectivity and convenience

- ***Connects separated locations:*** Bridges link two points separated by a river, valley, or other terrain, making travel possible where it would otherwise be impossible by boat or by taking a long detour.
- ***Saves time and distance:*** They provide a direct path, significantly reducing travel time and distance for both people and goods.
- ***Enables infrastructure development:*** They are crucial for building modern transportation systems, such as roads and railways, by allowing them to cross over other routes or geographical features.

Economic and social benefits

- ***Supports trade and economic growth:*** By facilitating the movement of goods and services, bridges boost economic activity and allow communities to access wider markets.
- ***Improves accessibility:*** They help people access essential services, jobs, and social opportunities in different areas.
- ***Fosters cultural exchange:*** Bridges can connect communities with different cultures, promoting understanding and interaction.

Safety and security

- ***Provides safe passage:*** They offer a safe way to cross dangerous obstacles like busy highways, railways, and deep rivers that would be hazardous to cross on foot or at ground level.
- ***Reduces accidents***: By providing dedicated crossing points, especially for pedestrians, bridges can reduce the risk of road traffic injuries and fatalities.

1.4 Parts of Bridges

Parts of Bridges – Superstructure and Substructure

Bridges are mainly divided into two major sections:

- ***Superstructure*** – the part above the foundation that carries traffic.
- ***Substructure*** – the part below the superstructure that supports and holds up.

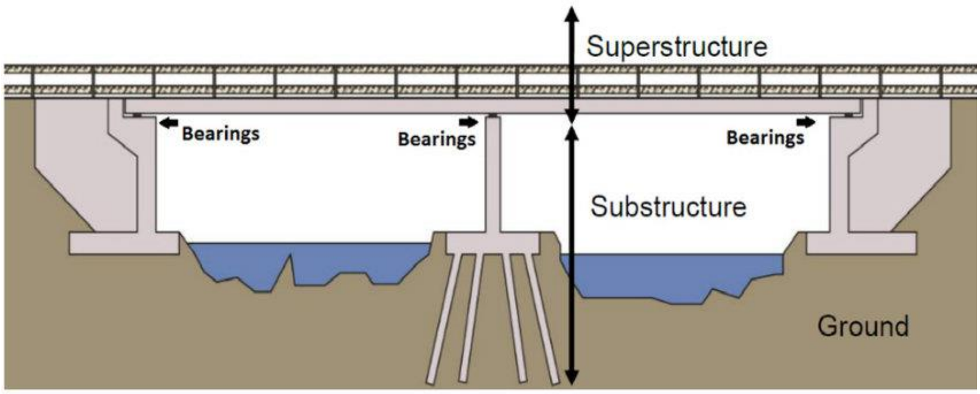


Fig.2 *Major sections of bridges*

1. Superstructure (Top Part of the Bridge)

This is the portion of the bridge that directly supports vehicles, people, and loads. It includes all components above the bearings.

Main Parts of the Superstructure:

• ***Deck***

The surface on which vehicles and pedestrians move.

• ***Girders / Beams***

Horizontal members that support the deck.

• ***Slab***

A flat concrete layer forming the deck surface (in concrete bridges).

• ***Trusses***

Framework of connected elements (in truss bridges).

• *Cables*

Used in suspension and cable-stayed bridges to hold up the deck.

• *Towers / Pylons*

Tall supports that hold the cables (in cable-supported bridges).

• *Arch*

Curved structure (in arch bridges) that carries loads through compression.

• *Bearings (sometimes considered part of superstructure)*

Allow movement between the deck and substructure.

2. Substructure (Bottom Part of the Bridge)

This is the portion that **supports** the superstructure and transfers loads safely to the ground.

Main Parts of the Substructure:

• *Abutments*

Support the ends of the bridge and hold back the soil of the approach roads.

• *Piers*

Vertical supports placed between abutments for longer bridges.

• *Columns*

Vertical structural elements (often part of piers).

• *Footings*

Wide, strong bases that spread the load from piers and abutments.

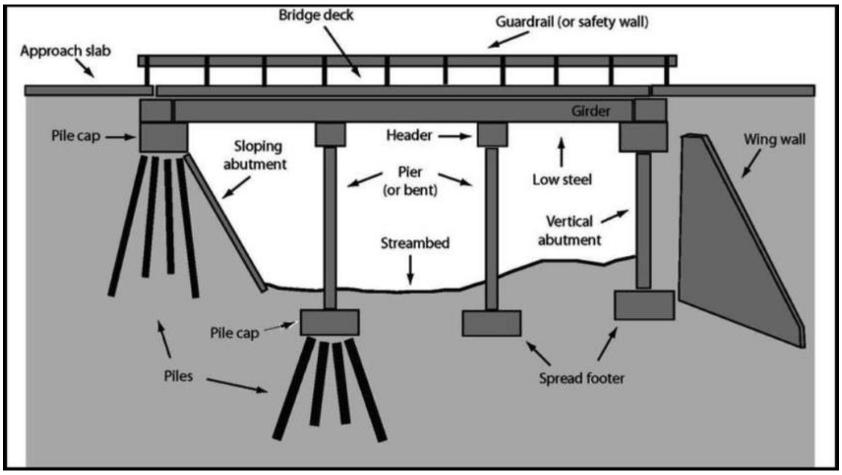


Fig.3 *Foundation view of bridge*

• ***Foundation***
The lowest part, usually below ground level, which transfers loads to the soil or rock beneath.

1.5 Types of Bridges

Bridges can be classified based on their **structure, materials,** or **function.** The most common way is by their **structural design**. Below are the major types:

1. Beam Bridge
The simplest type.
Consists of a horizontal beam supported at both ends.
Used for short spans (small distances).
Examples: small road bridges, flyovers.

2. Arch Bridge
Has a curved arch structure.
Strong and can carry heavy loads.
Transfers weight outward to supports (abutments).
Examples: stone bridges, old masonry bridges.

3. Truss Bridge
Made of a framework of triangular units.
Very strong and used for medium to long spans.
Economical and used for railways.

4. Suspension Bridge
Has cables suspended between tall towers.
Deck hangs from vertical cables.
Used for very long spans (long distances).
Examples: Golden Gate Bridge.

5. Cable-Stayed Bridge
Deck is directly supported by cables connected to towers.
Looks similar to suspension bridges but with a different cable pattern.
Suitable for medium to long spans.

6. Cantilever Bridge
Uses structures that project horizontally and are supported only on one end.
Good for medium spans.
Strong and stable.

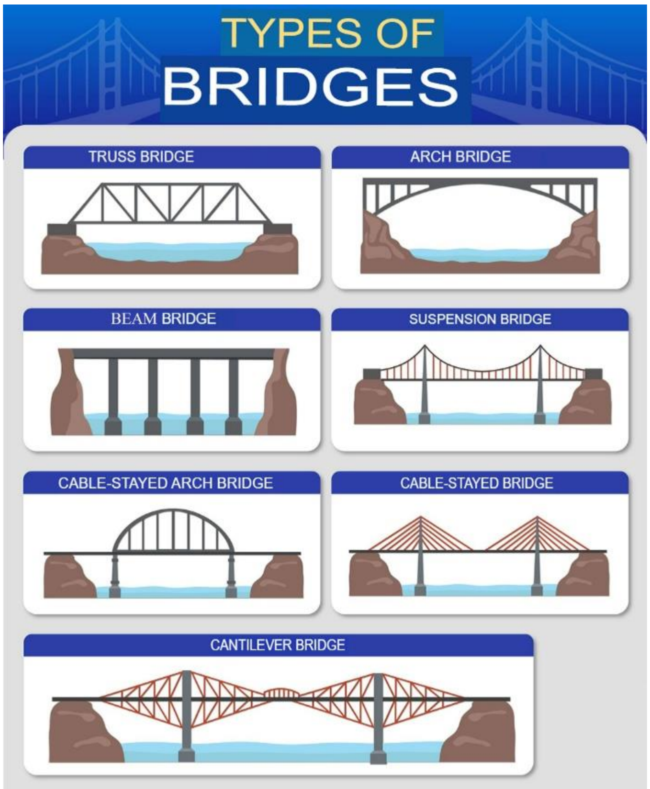


Fig.4 *Types of bridges*

1.6 Design of Bridges

Design process steps

1. ***Define the problem:*** Understand the purpose and requirements of the bridge.
2. ***Identify loads:*** Determine all the forces the bridge will experience. This includes dead loads (the bridge's own weight), live loads (traffic), and environmental loads (wind, snow, earthquakes).
3. ***Calculate the maximum load:*** Combine all potential loads to find the highest possible force the bridge must withstand.
4. ***Design the structure:*** Calculate the necessary size and shape of the components to resist the maximum load.
   A. Use formulas to relate force, material strength, and area to size beams and columns.
   B. For beams, calculations often depend on the span and length.
   C. For cable-stayed or suspension bridges, the design often uses tension forces to maximize material efficiency.

Factors to consider

- ***Engineering Requirements:*** Safety, strength, lifespan, climate, traffic, and the obstacle being crossed.
- ***Non-Engineering Requirements:*** Construction and maintenance costs, aesthetics, construction time, and local community impact.
- ***Materials:*** The choice of material, such as timber, steel, or concrete, affects the design and construction.
- ***Environmental impact:*** The effect on wildlife and the local environment is a key consideration.

2. SEISMIC ANALYSIS

2.1 Earthquakes

An **earthquake**, also called a **quake**, **tremor**, or **temblor**, is the shaking of the Earth's surface resulting from a sudden release of energy in the lithosphere that creates seismic waves. Earthquakes can range in intensity, from those so weak they cannot be felt, to those violent enough to propel objects and people into the air, damage critical infrastructure, and wreak destruction across entire cities. The seismic activity of an area is the frequency, type, and size of earthquakes experienced over a particular time.

In its most general sense, the word *earthquake* is used to describe any seismic event that generates seismic waves. Earthquakes can occur naturally or be induced by human activities, such as mining, fracking, and nuclear weapons testing. The initial point of rupture is called the hypocentre or focus, while the ground level directly above it is the epicentre. Earthquakes are primarily caused by geological faults, but also by volcanism, landslides, and other seismic events.

2.2 Effects of Earthquakes on Bridges

Earthquakes can cause serious damage to bridges because they shake the ground suddenly and violently. Bridges are long, rigid structures, so when the ground moves beneath them, different parts of the bridge may move in different directions. This can lead to structural failure if the bridge is not designed to withstand seismic forces.

1. Ground Shaking

Ground shaking is the main cause of damage.

- The **deck**, **piers**, and **abutments** move differently.
- This creates **stress**, **cracks**, or **tilting**.
- Long bridges experience **vibration** that can damage joints and bearings.

2. Foundation Failure

Earthquakes can weaken the soil under bridge foundations.
Liquefaction (when loose, water-soaked soil behaves like liquid) can cause piers to sink or tilt.
Weak foundations may crack or collapse.

3. Damage to Piers and Columns

Piers are vertical supports; they face high bending and shear forces during earthquakes.
Cracking
Spalling (breaking of concrete surface)
Complete collapse if forces exceed capacity

Fig.5 *View of Damage to piers and columns*

4. Deck Movement and Failure

- The bridge deck may slide or fall from its supports.
- Earthquake shaking can cause **unseating**, where the deck slips off the piers.
- Expansion joints may break or get jammed.

5. Cable and Tower Damage (for cable-stayed and suspension bridges)

- Towers may sway and crack.
- Cables may experience excessive tension.
- Uneven movement can damage anchorages.

6. Damage to Bearings

Bearings allow controlled movement between deck and piers.

- Earthquakes can make bearings **fail**, **dislocate**, or **break**.
- This reduces the ability of the bridge to absorb movements.

2.3 Real-life Examples

1) **Loma Prieta Earthquake, 1989 (California, USA)**
   Cypress Street Viaduct collapsed due to **pier failure**.
2) **Kobe Earthquake, 1995 (Japan)**
   Many elevated highways and bridges suffered **deck unseating and pier collapse**.
3) **Christchurch Earthquake, 2011 (New Zealand)**
   Several bridges had **foundation and pier damage** due to liquefaction.

Fig. *6 Loma Priesta Earthquake,1989*

Fig. *7 Kobe Earthquake, 1995*

2.4 Measures to Make Bridges Earthquake-Resistant

Bridges are vulnerable to earthquakes due to ground shaking, differential movement, and soil failure. Modern engineering uses design, materials, and construction techniques to minimize damage and ensure safety.

1. Seismic Isolation

- **Isolation bearings** are placed between the deck and piers/abutments.

- They allow controlled movement of the deck during shaking, reducing stress on the structure.
- Types include **elastomeric bearings** and **sliding bearings**.

2. Ductile Design of Piers and Columns

- Piers and columns are designed to **bend without breaking** (ductility).
- Reinforced concrete and steel are used to absorb energy.
- **Plastic hinges** are allowed in controlled locations to dissipate seismic energy safely

3. Strong Foundations

- Foundations are designed to **resist shaking and liquefaction**.
- Options include **deep pile foundations**, **caissons**, or **spread footings** depending on soil type.
- Soil improvement techniques (compaction, grouting) may be used in weak soils.

4. Proper Bearing and Expansion Joint Design

- Bearings and expansion joints accommodate **deck movements** during earthquakes.
- Prevent **deck unseating** and reduce damage to superstructure.
- Use of **restrainers** or **stop blocks** can limit excessive sliding.

5. Energy Dissipation Devices

- Dampers absorb vibration energy and reduce oscillations in the bridge.
- Types include:
    - ❖ **Viscous dampers**
    - ❖ **Friction dampers**
    - ❖ **Tuned mass dampers**

6. Flexible and Redundant Structural Design

- Avoid overly stiff designs that fail suddenly.
- Multiple load paths ensure that if one part fails, the bridge still remains stable.

- Use **continuous spans** or **redundant members** for strength.

7. Cable-Stayed and Suspension Bridge Measures

- Towers designed to **sway safely**
- Cables designed for **tension fluctuations**
- Decks anchored and restrained to prevent large displacements

8. Regular Inspection and Retrofitting

- Existing bridges are assessed and strengthened using:
  - ❖ **Jacketing of columns**
  - ❖ **Base isolation retrofits**
  - ❖ **Addition of restrainers or dampers**
- Ensures older bridges can withstand modern seismic standards.

9. Site-Specific Measures

- Avoid construction on **soft, liquefiable soil** when possible.
- Conduct **geotechnical studies** before building.
- Stabilize slopes to prevent **earthquake-induced landslides** near bridges

3. WIND LOAD

Wind load is the force exerted by wind on a bridge structure. It is an important factor in bridge design because bridges are **long, slender, and exposed**, making them sensitive to wind effects. Wind can cause **vibration, swaying, or even structural failure** if not properly accounted for.

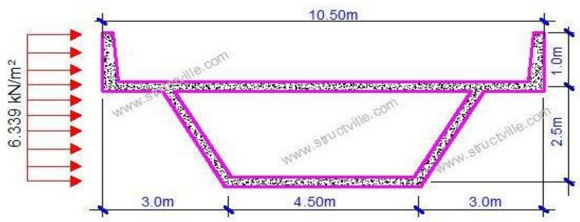


Fig.*8 View of wind load force on bridge structure*

3.1 Application of Wind load on bridges

Wind load is a critical factor in bridge design and analysis, especially for long-span, tall, or flexible bridges such as suspension and cable-stayed bridges. Engineers must account for wind forces to ensure safety, stability, and comfort.

1. Design Considerations

Wind load is applied in bridge design to calculate the **lateral and vertical forces** acting on various components:

- ***Deck****:* Wind exerts **horizontal pressure**, causing swaying or twisting.
- ***Piers / Towers****:* Tall structures experience **lateral bending**.
- ***Cables****:* For cable-stayed or suspension bridges, wind can create **vibration in cables**.
- ***Bearings and joints****:* Must accommodate lateral movement induced by wind.

Engineers use **codes and standards** (like AASHTO, IS 875 Part 3 in India) to determine wind pressure based on location, height, and shape of the bridge.

2. Types of Wind Effects Considered

1. ***Static Wind Pressure***
   - Constant wind force acting sideways on the bridge structure.
   - Used to design **piers, towers, and decks**.
2. ***Dynamic Effects***
   - **Vortex shedding**: Alternating forces that cause lateral vibration.
   - **Flutter**: Aerodynamic twisting that can destabilize the bridge deck.
   - **Galloping / buffeting**: Oscillations due to gusty winds.

3. ***Combined Effects***
   - Wind is considered **along with traffic load, seismic load, and temperature effects** for overall design.

3. Application in Bridge Design

- ***Structural Analysis:*** Wind load is applied in calculations to check **stress, bending, torsion, and vibration**.
- ***Safety Margins:*** Factors of safety are included to account for extreme winds.
- ***Aerodynamic Optimization****:* Shape of the deck, piers, and towers is designed to reduce wind forces.

- ***Use of Dampers and Stiffening**:* Devices are installed to mitigate vibrations caused by wind.

4. Examples

- ***Suspension Bridges**:* Deck and cables designed for flutter and vortex-induced vibrations.
- ***Cable-Stayed Bridges**:* Towers and cables analysed for lateral sway under wind gusts.
- ***Beam or Truss Bridges**:* Wind load used to design piers and lateral bracing.

3.2 Real-Life Examples of Wind Load on Bridges

1. Tacoma Narrows Bridge, USA (1940)

- Type: Suspension bridge
- Location: Puget Sound, Washington
- Incident: Collapsed just 4 months after opening.
- Cause: Strong winds (~40 mph) caused aeroelastic flutter (torsional oscillation)
- Lesson: Importance of aerodynamic deck design and torsional stiffness.

***Fig.**9 Tacoma Narrows Bridge, USA (1940)*

2. Bronx–Whitestone Bridge, USA (1940s–1950s)

- Type: Suspension bridge
- Location: New York City
- Incident: Deck experienced excessive lateral vibrations under wind.
- Solution: Installed stiffening trusses to reduce deck oscillations.

3. Severn Bridge, UK (1966)

- Type: Suspension bridge
- Location: England-Wales
- Incident: Strong winds caused deck vibration and lateral movement during early operations

- Solution: Aerodynamic modifications and dampers were installed.

4 MOVING LOAD

A **moving load** is the load applied to a bridge by vehicles, trains, pedestrians, or other moving objects. Unlike **static loads**, which remain in a fixed position, moving loads **change location over time**, causing varying stresses in the bridge structure.

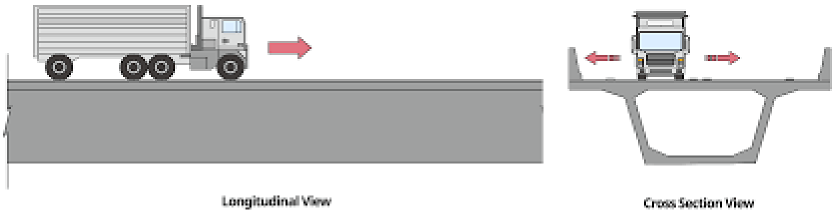


Fig. *10 Moving load view on bridge structure*

4.1 Types of Moving Loads

1 ***Vehicular Load***

- Cars, trucks, buses, or other road vehicles.
- Load varies in **magnitude, axle spacing, and position**.

2 ***Railway Load***

- Trains are heavier than road vehicles and can create **significant dynamic effects**.
- Includes **axle load, spacing, and train speed**.

3 ***Pedestrian Load***

Foot traffic can cause **localized vibrations**, especially on footbridges.

4 ***Wind, Earthquake, or Other Moving Environmental Loads***

Considered dynamic loads in some bridge analyses.

4.2 Effects of Moving Loads

- ***Bending Moment:*** Maximum bending occurs at the span where the load is applied.
- ***Shear Force:*** Shear changes along the bridge as the load moves.
- ***Deflection:*** Bridges bend or sag under moving loads; magnitude depends on speed and span length.
- ***Dynamic Amplification:*** Fast-moving vehicles or trains can increase stresses beyond static calculations.

5 LITERATURE REVIEW:

5.1. Literature 'Types of Bridges structural systems'

Bridge structural systems define the mechanisms by which loads are transferred through the superstructure to the substructure, ultimately ensuring stability, serviceability, and durability of the crossing. The selection of an appropriate structural system is influenced by span length requirements, material availability, geotechnical conditions, aesthetic considerations, construction methods, maintenance expectations, and economic constraints (Chen & Duan, 2014). Beam bridges, often considered the most fundamental system, rely on bending resistance and shear capacity, making them suitable for short to medium spans where simplicity and cost-effectiveness are priorities. Truss bridges, composed of interconnected triangular units, efficiently distribute forces through axial tension and compression, allowing for longer spans and reduced material usage (Smith, 2018). Arch bridges utilize the natural capacity of the arch form to carry loads primarily in compression, enabling the structure to span significant distances while offering exceptional rigidity and appealing architectural expression.

For sites where long spans must be achieved without intermediate supports—such as deep valleys or navigable waterways—cantilever bridges provide an effective solution by enabling construction from piers outward, minimizing the need for temporary falsework. In contrast, suspension bridges employ large main cables draped over towers, transferring loads to robust anchorages. This configuration allows for some of the longest spans in the world while accommodating dynamic loads such as wind and traffic. Similarly, cable-stayed bridges support the deck directly through inclined cables connected to one or more towers, offering efficient load paths, reduced material use compared to suspension systems, and considerable flexibility in architectural form (Ghosh & Jain, 2020).

Contemporary bridge engineering also integrates advanced materials—such as high-performance concrete, weathering steel, and fiber-reinforced polymers—with computational design tools and construction innovations, leading to hybrid systems and optimized structural configurations. Environmental considerations, life-cycle cost analysis, seismic performance, and resilience against extreme events increasingly shape system selection. As a result, modern bridge design represents a synthesis of structural mechanics, aesthetics, sustainability, and practical constraints, ensuring that chosen systems meet both present functional demands and long-term societal needs.

- ***Beam (Girder) Bridges***

  Beam bridges are the simplest and most widely used structural system. The deck is supported by girders, and loads are carried through bending and shear, with the top fibers in compression and bottom fibers in tension. They are most suitable for short to medium spans and commonly constructed using reinforced concrete, prestressed concrete, or steel.

- ***Truss Bridges***

  Truss bridges consist of interconnected members forming triangular units. This arrangement ensures that loads are carried as axial forces—either tension or compression—making trusses highly efficient for medium to long spans. They are especially common in railway bridges due to their strength and rigidity.

- ***Arch Bridges***

  Arch bridges derive their strength from a curved form that carries loads predominantly through compression. The arch thrust is resisted by strong abutments at each end. This system is ideal for medium to long spans, particularly in areas where natural supports or strong foundations exist. Variants include deck arch, through arch, and tied-arch bridges.

- ***Cantilever Bridges***

  Cantilever bridges use projecting beams or truss arms supported at only one end. These arms can extend from both sides and connect at the center, creating a long span without requiring supports in deep water or difficult terrain. Loads induce significant bending moments, which are resisted by the fixed supports.

- ***Suspension Bridges***

  Suspension bridges are used for the longest spans. The deck is supported by vertical hangers attached to main cables, which transfer loads through tension to the towers (in compression) and anchorages (resisting horizontal pull). This system provides exceptional flexibility and span capacity.

- ***Cable-Stayed Bridges***

  In cable-stayed bridges, the deck is directly supported by multiple straight stays connected to one or more towers. The stays carry tension, while the towers resist compression. This system is efficient for medium to long spans and provides high stiffness along with architectural elegance. Cable arrangements include harp and fan systems.

5.2 Literature on 'Analysis of Cable Bridges'

Cable-stayed bridges have been widely studied in structural engineering literature due to their efficient load-carrying mechanism, aesthetic appearance, and applicability for long spans. The analysis of these bridges has evolved significantly with advancements in computational tools, material technology, and understanding of cable-structure interaction (Gimsing & Georgakis, 2012). Researchers have examined key aspects such as structural behaviour, dynamic response, cable mechanics, construction stage effects, and long-term performance.

Early research focused on simplified analytical models that treated cables as linear elements and the deck as a beam supported by inclined stays. These studies laid the foundation for understanding global behaviour but did not capture nonlinearities. With the development of finite element methods (FEM), more comprehensive models incorporating geometric nonlinearity, cable sag, and material properties became possible. Literature shows that the nonlinear behaviour of cables, particularly catenary action, significantly affects bridge stiffness and internal force distribution. The introduction of the Ernst modulus improved the accuracy of linearized cable models and remains widely used for preliminary analysis (Ernst, 1965).

A major area of research concerns dynamic behaviour, especially wind-induced effects. Numerous studies highlight that cable-stayed bridges are highly sensitive to wind because of their lightweight deck, tall pylons, and flexible cable systems (Xu & Xia, 2011). Phenomena such as vortex shedding, flutter, buffeting, and rain-wind induced vibrations are common topics. Researchers have proposed multiple damping solutions, including viscous dampers, tuned mass dampers (TMDs), and cross-tie systems to reduce cable vibrations. Modal analysis literature shows that pylons dominate the fundamental vibration modes, while cables influence higher-frequency modes.

Seismic performance forms another major segment of analytical research. Because of their long spans and flexible structural components, cable-stayed bridges exhibit complex behaviour under earthquakes. Studies emphasize the importance of multi-support excitation, pylon flexibility, and cable–deck interaction. Numerical investigations reveal that seismic forces redistribute significantly due to geometric nonlinearities and coupling effects. Recent literature also explores base isolation, energy dissipation devices, and viscoelastic dampers to enhance seismic resilience (Chen & Duan, 2014).

Cable arrangement is an important design parameter frequently analysed in research. Comparative studies evaluate fan, harp, and semi-fan configurations and show that the semi-fan system often provides the most balanced axial-force distribution. The choice of arrangement affects deck bending, cable stress levels, and pylon behaviour. The inclination angle, spacing, and anchoring position of cables are also extensively studied, revealing their impact on global stiffness and vibration characteristics.

Another key area in literature is deck behaviour. Analytical models indicate that deck stiffness directly influences forces in cables, bending moments, and deflection patterns. Studies comparing steel, concrete, and composite decks show that composite decks provide improved stiffness and better control of vibrations. Researchers also explore the connection details between the deck and pylons to optimize load transfer.

Analytical work also emphasizes the significance of construction stage analysis. Since cable-stayed bridges are typically built using the cantilever method, the structural system undergoes continuous change during construction. Literature highlights that ignoring staged construction can result in inaccurate estimation of final stresses, cable forces, and deck geometry. Detailed studies examine cable stressing procedures, the use of temporary supports, and sequential loading.

Long-term behaviour is another frequently examined topic. Material-related phenomena such as creep and shrinkage in concrete pylons and relaxation in stay cables cause gradual redistribution of internal forces. Literature indicates that these time-dependent effects must be incorporated to ensure accurate prediction of bridge performance throughout its service life. Fatigue behaviour of cables under repetitive live loads and wind is another recurring subject in long-term studies.

Recent advancements include the use of structural health monitoring (SHM) systems, where sensors such as accelerometers, strain gauges, GPS receivers, and cable force sensors are installed on real bridges. These monitoring systems provide data for validating analytical models and improving the accuracy of dynamic and static predictions. Model updating techniques help improve reliability and safety assessment.

Many comparative studies also evaluate differences between cable-stayed and suspension bridges. Cable-stayed bridges generally exhibit higher stiffness and better control of deck deflections, while suspension bridges perform better for extremely long spans. Literature stresses that cable-stayed bridges are more sensitive to pylon deformation because loads are carried directly to the towers through inclined cables.

Overall, literature on cable-stayed bridge analysis highlights a multi-disciplinary approach involving nonlinear structural behaviour, dynamic and seismic analysis, wind engineering, material time-dependent effects, construction simulation, and long-term monitoring.

Continuous improvements in computational modelling and data-driven techniques have significantly enhanced the understanding of the performance of cable-stayed bridges, making them safer, more efficient, and more reliable for modern long-span applications.

5.3 Literature on 'Seismic Analysis of Bridge'

The seismic analysis of bridges has evolved significantly, transitioning from traditional **Force-Based Design (FBD)** to more advanced **Displacement-Based Design (DBD)** to better represent **inelastic behavior** during strong earthquakes *(Priestley et al., 1996)*. Modern literature emphasizes **performance-based engineering**, **nonlinear modeling**, and accurate prediction of **deformation capacity**. The most authoritative references include major design codes, federal manuals, and foundational textbooks.

Key design codes such as the AASHTO **Guide Specifications for LRFD Seismic Bridge Design**, **AASHTO LRFD Bridge Design Specifications**, and **Eurocode 8 (Part 2: Bridges)** provide comprehensive guidelines on seismic analysis procedures *(AASHTO, 2020)*. These documents highlight the use of response spectrum methods, ductility requirements, and nonlinear verification through pushover and time-history analysis. AASHTO's seismic guide marks a shift toward capacity design principles and performance objectives based on Seismic Design Categories (SDC).

Foundational academic literature, including the FHWA LRFD Seismic Analysis and Design Manual, explains engineering seismology, structural dynamics, and application of modern design theories. The work of **Priestley, Seible, and Calvi** is widely recognized for establishing DBD and detailing requirements for **ductile behavior** *(Priestley et al., 2007)*. For theoretical background, **Chopra's Dynamics of Structures** serves as the primary source for understanding modal analysis, response spectra, and nonlinear dynamic response.

Analytical methods extensively discussed in literature include both **linear elastic** and **nonlinear procedures**. Linear methods, such as **Equivalent Static Analysis** and **Response Spectrum Analysis**, are used for simpler bridges and lower seismic zones. For complex or high-importance bridges, **Nonlinear Static (Pushover)** and **Nonlinear Time History Analysis (NTHA)** are preferred due to their ability to capture **plastic hinging**, **energy dissipation**, and **true inelastic response**.

Modeling considerations form a major theme in research. Studies emphasize the importance of soil–structure interaction (SSI), as soil flexibility alters the fundamental period and force distribution of bridges. Accurate nonlinear modeling of piers, bearings, abutments, and seismic isolation devices is essential for realistic response prediction. Literature also highlights the significance of material nonlinearity, particularly moment–curvature relationships for concrete columns and behavior of confined vs. unconfined concrete.

Overall, existing literature shows that modern seismic bridge analysis requires a combination of **rigorous theoretical understanding**, **realistic modeling**, and **performance-based evaluation** to ensure **safety and resilience** during major earthquakes.

5.4 Literature on 'Different Cable Materials'

The selection of cable material remains one of the most decisive factors in the engineering of long-span bridges because it fundamentally affects **structural efficiency**, **deflection behavior**, **durability**, **safety**, and **long-term maintenance strategies**. The literature presents a well-documented evolution of cable materials—from early wrought iron, through high-strength steel, to emerging fiber-reinforced polymer (FRP) systems—each stage influenced by advancements in materials science, structural demands, and performance expectations.

Historically, wrought iron chains provided the first practical means of constructing suspension bridges, yet their low tensile strength, inconsistent material quality, and vulnerability to environmental degradation limited their use as spans increased. The advent of **high-strength steel wire ropes** marked a transformative period. Steel became the global standard due to its **high tensile capacity**, predictable mechanical properties, economic feasibility, and well-developed manufacturing techniques *(Gimsing & Georgakis, 2012)*. Literature emphasizes that steel cables, despite their advantages, face persistent issues such as **corrosion, fatigue, stress relaxation, hydrogen embrittlement**, and difficulties in detecting internal wire fractures *(Shi et al., 2009)*. These concerns have driven continuous innovation in protective methods—including **galvanization, epoxy coating, wax injection, pressurized-dehumidification systems**, and **advanced non-destructive evaluation (NDE)** techniques such as magnetic flux leakage, guided wave ultrasonics, and acoustic emission monitoring.

More recent research points to **FRP composite cables**—particularly those using carbon (CFRP), aramid (AFRP), and glass fibers (GFRP)—as promising alternatives for future long-span bridges. FRP cables offer **high strength-to-weight ratios**, excellent **corrosion resistance**, and reduced **dead load**, which improve aerodynamic stability and lower demands on towers and foundations *(Karbhari & Zhao, 2007)*. However, their implementation introduces new challenges, including **viscoelastic behavior, long-term creep, UV degradation, temperature sensitivity**, uncertainties in fire performance, and the absence of universally accepted design standards. Anchoring FRP cables remains a key technical challenge due to their **anisotropic, non-ductile behavior** and sensitivity to stress concentrations. Research continues to explore specialized anchor systems, resin matrices with improved thermal stability, and **hybrid fiber arrangements** to mitigate these issues.

Recent literature also highlights the emergence of **hybrid cable systems**, where steel and FRP components are combined to achieve an optimized balance of **strength, ductility, corrosion resistance**, and cost. Such hybrid solutions aim to exploit the complementary benefits of each material while reducing their respective limitations. Additionally, progress in manufacturing techniques, including **pultrusion for FRP tendons**, **precision wire drawing**, and **automated cable spinning systems**, has been crucial in improving material consistency, structural reliability, and construction efficiency.

Environmental and sustainability considerations have become increasingly significant. Steel production is **energy-intensive** and contributes substantially to carbon emissions, while FRP manufacturing raises concerns related to **recyclability** and **end-of-life disposal**. **Life-cycle assessment (LCA)** studies play a growing role in evaluating trade-offs among **initial cost, durability, maintenance requirements, and environmental impact**. Furthermore, resilience under **extreme events**—including earthquakes, wind storms, temperature extremes, and fire—now features prominently in material selection research.

Digital technologies are also influencing cable selection. **Smart cable systems** equipped with **fiber optic sensors**, strain gauges, or self-monitoring resins enable continuous **structural health monitoring (SHM)**, early detection of deterioration, and predictive maintenance. These innovations reduce lifecycle uncertainty and support data-driven decision-making for long-span bridge management.

Overall, contemporary literature underscores that **cable material selection extends far beyond tensile strength**; it reflects a holistic consideration of **structural performance, durability, constructability, economic feasibility, environmental impact**, and **long-term resilience**. As bridges continue to push the boundaries of span length and architectural expression, advancements in cable materials—and the technologies that support them—will remain central to enabling the next generation of long-span bridge engineering.

5.5 Literature Summary

Extensive research has been carried out on major bridge structural systems such as beam, truss, arch, suspension, and cable-stayed bridges, particularly focusing on their load response, structural behavior, and fundamental mechanics. However, most studies analyze each system independently, which results in insufficient comparative understanding of long-term performance and sustainability. Hybrid systems like extradosed and stress-ribbon bridges are still underrepresented in scholarly work, as highlighted by Tang & Podolny (2015). In the case of cable-stayed bridges, the literature largely emphasizes global behavior, construction stage analysis, nonlinear cable mechanics, and wind effects, but areas such as deterioration, real-time cable behavior, temperature-induced stresses, and interaction between deck, cables, pylons, and soil need further attention (Chen & Duan, 2020). Modern digital technologies, such as AI-based prediction, digital twins, and sensor-driven model updating, are rarely integrated, limiting the transition from theoretical development to practical implementation.

- Most literature studies each bridge type separately instead of offering integrated comparisons.
- Long-term performance, durability, and environmental effects are insufficiently examined across structural systems.
- Hybrid bridges (extradosed, stress-ribbon) lack detailed long-term behaviour research.
- Cable-stayed bridge studies emphasise nonlinear mechanics, wind effects, and global behaviour.
- Limited research exists on deterioration, real-time cable relaxation, thermal behaviour, and soil–structure interaction.
- Integration of digital technologies (AI, SHM, real-time monitoring) in analytical models is still lacking.

Research on seismic behavior of bridges has advanced toward nonlinear, displacement-based, and multi-support excitation models. Near-fault ground motion, soil liquefaction, and pylon dynamics are increasingly evaluated in academic work, but practical design standards have yet to fully adopt these findings (Priestley et al., 2007). Post-earthquake aspects such as damage evaluation, repair strategies, and rapid recovery for long-span bridges remain inefficiently addressed. Similarly, while studies on cable materials indicate that FRP systems offer high corrosion resistance and strength-to-weight benefits, uncertainties remain regarding anchorage behavior, fire resistance, hybrid cable performance, and long-term durability (Nakamura et al., 2019). Overall, the literature shows that multi-hazard, life-cycle based, and interdisciplinary analytical models are still lacking, and comprehensive performance-based and data-driven approaches are crucial for enhancing safety and service life of modern bridge systems.

- Nonlinear and displacement-based seismic analysis is well developed, yet underutilised in practice.

- Limited incorporation of near-fault effects, multi-support excitation, and soil liquefaction into design.
- Lack of studies on post-earthquake resilience, repair strategies, and rapid recovery for long-span bridges.
- FRP cable research shows promise but lacks long-term real-world performance data.
- Comparative studies between steel, CFRP, GFRP, AFRP, and hybrid cables are limited.
- Multi-hazard analysis combining wind, earthquake, temperature effects, traffic loads, and ageing is rarely studied.
- Few models integrate life-cycle assessment, sustainability, monitoring data, and advanced material behaviour.

5.6 Literature Gap

Although extensive research exists on bridge structural systems, the analysis of cable-stayed bridges, seismic behaviour, and advanced cable materials, several significant gaps still remain in the existing body of knowledge. Much of the available literature focuses on isolated mechanisms of behaviour, whereas integrated, multi-hazard, and long-term performance assessments remain limited. Most studies investigate traditional structural systems—beam, truss, arch, suspension, and cable-stayed bridges—independently, without sufficiently comparing their load-response characteristics, redundancy levels, resilience under environmental degradation, or life-cycle behaviour. In addition, emerging hybrid bridge forms such as extradosed and stress-ribbon systems remain underrepresented in rigorous analytical and experimental studies, resulting in limited understanding of their load distribution, fatigue performance, and long-term serviceability.

In the analysis of cable-stayed bridges, the literature provides a strong basis for understanding global structural behaviour and wind–cable interaction; however, critical issues remain insufficiently explored. These include construction stage analysis, which strongly influences final stress states, long-term deterioration of cables and pylons, corrosion effects, relaxation of stays, and combined time-dependent behaviour such as creep and shrinkage. The interaction between cables, pylons, deck, and foundations under combined traffic, wind, temperature, and seismic loading is still poorly understood. Similarly, soil–structure–cable interaction, especially under dynamic loads or seismic excitation, has not been comprehensively incorporated into most analytical models. Moreover, despite advances in digital technologies, most studies do not leverage AI-based damage prediction, machine-learning-driven model updating, digital twin systems, or SHM-integrated numerical frameworks, creating a gap between academic research and practical monitoring needs.

Despite advances in seismic analysis—such as nonlinear dynamic analysis, displacement-based methods, and pushover modelling—current practical design frameworks still do not fully incorporate the latest research outcomes. Critical aspects such as multi-support excitation effects, traveling wave phenomena, vertical ground motion components, near-fault velocity pulses, and soil liquefaction-induced displacements remain insufficiently integrated in bridge design. Long-span bridges, in particular, are sensitive to spatial variability of ground motion, yet few studies address these complex interactions. Additionally, research on post-earthquake repairability, rapid restoration strategies, redundancy loss, and long-term resilience of cable-supported and hybrid bridges is still limited. Most studies emphasize strength and displacement capacity, whereas functionality, downtime, and life-cycle seismic fragility remain largely unexplored.

In the area of cable materials, while steel, CFRP, AFRP, and other FRP systems have received significant attention, major gaps persist. Long-term issues such as creep rupture in FRPs, fire resistance, UV degradation, moisture absorption, and thermal ageing are not fully established. Most published studies are based on laboratory-scale tests, with very limited full-scale field monitoring and long-term case studies for cable-stayed or suspension bridges using composite cables. Research on hybrid cable systems, combining steel and FRP, is still in the early stage, and questions remain regarding compatibility of stiffness, differential ageing, fatigue resistance, anchorage performance, and behaviour under combined extreme loads. Environmental sustainability is another underexplored area, with insufficient literature on recyclability, embodied energy, carbon footprint, and life-cycle cost comparisons between traditional steel systems and emerging FRP technologies.

Across these domains, an overarching gap is the absence of holistic, multi-disciplinary, and multi-hazard analytical frameworks that integrate:

- structural system behaviour
- material degradation
- seismic performance
- aerodynamic behaviour
- construction sequencing
- soil–foundation interaction
- Advanced monitoring technologies
- long-term sustainability considerations.

Although extensive research has been carried out on bridge structural systems and long-span behaviour, several critical gaps still remain unaddressed. Studies by Chen and Duan (2014) and Gimsing and Georgakis (2012) provide strong foundations for understanding different bridge types, yet comparative, multi-hazard, and life-cycle evaluations of beam, arch, suspension, and cable-stayed systems are still limited. Research on cable-stayed bridges by Virlogeux (1999) and Abdel-Ghaffar (1991) mainly focuses on global structural response and wind behaviour, leaving gaps related to deterioration, soil–structure interaction, real-time performance, and construction stage effects. Similarly, although seismic behaviour of bridges has evolved through nonlinear approaches (Priestley et al., 1996; Kawashima, 2012), there is insufficient integration of multi-support excitation, near-fault ground motions, and long-term degradation into practical design models. Regarding materials, studies by Meier (1995) and Karbhari (2007) highlight the advantages of steel and FRP cable systems, but long-term performance issues such as hybrid cable behaviour, anchorage reliability, durability under combined loads, and environmental impacts remain underexplored. Overall, despite progress in digital modeling and structural monitoring (Li & Ou, 2011), there is a lack of holistic, multidisciplinary, and data-driven frameworks that integrate structural system behaviour, advanced materials, multi-hazard actions, and long-term resilience, demonstrating a clear need for more comprehensive and performance-based research.

Most current studies address these aspects independently, whereas modern bridges experience simultaneous and interacting demands. Addressing these deficiencies requires performance-based, data-driven, and digitally enhanced research methodologies, combining advanced computational models, AI-driven prediction tools, probabilistic life-cycle assessment, and real-time monitoring systems to improve the safety, durability, and sustainability of long-span bridge infrastructure.

6. OBJECTIVES

The primary goal of this project is to conduct a comparative structural analysis of a cable-stayed bridge to evaluate the performance and suitability of different stay-cable materials under complex loading conditions, with a strong focus on seismic resilience.

The specific objectives of this study are:

1. ***Modeling and Analysis*****:** To accurately model a standard cable-stayed bridge structure using professional finite element software (STAAD.Pro) and apply combined design loads, including Dead Load, Wind Load, and Earthquake (Seismic) Load, as per relevant design codes.
2. ***Material Performance Comparison*****:** To analyze and compare the structural response of the bridge when utilizing five distinct cable materials: traditional Steel Tendons and four types of Fiber Reinforced Polymer (FRP) materials (AFRP, BFRP, CFRP, and GFRP).
3. ***Seismic Vulnerability Assessment*****:** To quantify the structural demand across all key components—the main girder (Beam End Forces), the deck plate (Plate Center Stresses), and the foundation (Support Reactions)—and identify the material that most effectively mitigates inertial forces generated during seismic events.
4. ***Structural Efficiency Determination*****:** To determine the most structurally efficient cable material by comparing the reduction in internal forces and stresses against the respective material properties (e.g., strength-to-weight ratio).
5. ***Lifecycle Cost Evaluation and Recommendation*****:** To provide an engineering recommendation by assessing the long-term economic viability and maintenance implications (Lifecycle Cost Analysis) of each cable material in conjunction with its demonstrated structural performance.

7. MATERIALS AND METHODOLOGY

7.1 Bridge Specifications and StaadPro Software

The cable-stayed bridge was modelled and analysed using STAAD.Pro Connect Edition, a structural analysis software by Bentley Systems known for its 3D modelling, finite element capabilities, and code-based design accuracy.

The bridge has a main span of 64 meters and an open deck supported by symmetrically arranged stay cables. The deck, designed for vehicular traffic, is 64 m long and 6 m wide, modelled using 64 rectangular plate elements (each 2 m × 3 m) with a thickness of 0.135 m. The deck transfers loads to the pylons through the stay cable system.

Four reinforced concrete pylons, each 8.5 m above the deck, anchor a total of 64 stay cables. The cables, modelled as tension-only circular steel members with a diameter of 0.089 m, are anchored at 0.5 m vertical intervals in a fan-type arrangement for uniform load distribution. The bridge is supported by ten concrete piers, each 12 m high, with circular members of 1.0 m diameter, with five piers on either side of the main span. These are modelled with fixed supports to ensure stability and effective load transfer to the foundation.

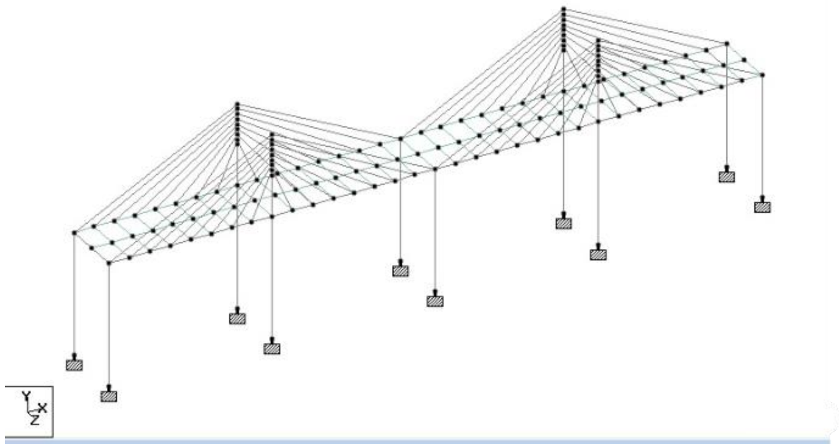


Fig.11 *3D model of cable-stayed bridge analysed using STAAD Pro*

Structural components were assigned appropriate material and geometric properties: the deck slab used M30 concrete, and rectangular beams of 0.5 m × 0.5 m. Loads applied included dead load, wind load, earthquake load, vehicle loads, and standard code combinations.

The structure was analysed for member forces, moments, support reactions, deflections, plate stresses and base pressure. The rendered 3D model in STAADPro, shown in Fig.___ illustrates the bridge geometry and provides realistic insights into its load-carrying behaviour.

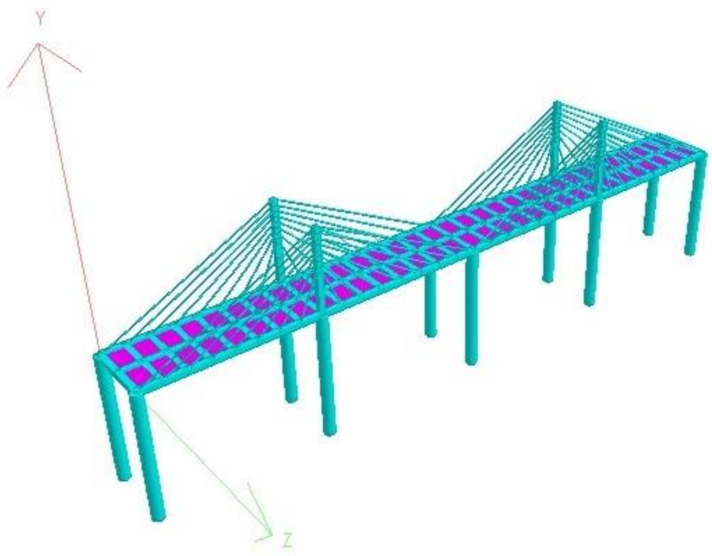


Fig.12 *Software Rendered View of the bridge model*

7.2 Materials Taken for Study

A. Carbon Fibre Reinforced Polymer (CFRP)

Carbon Fibre Reinforced Polymer (CFRP) is a lightweight composite material consisting of carbon fibres embedded in a polymer matrix, widely used in modern bridge engineering, including stay cables of cable-stayed bridges. In such applications, CFRP cables offer high tensile strength (600–4000 MPa), low density, and excellent corrosion and fatigue resistance, making them superior to traditional steel cables, especially in aggressive environments. Their high stiffness-to-weight ratio reduces overall dead load and enhances bridge durability. CFRP cables are also non-corrosive, require minimal maintenance, and have a long service life.

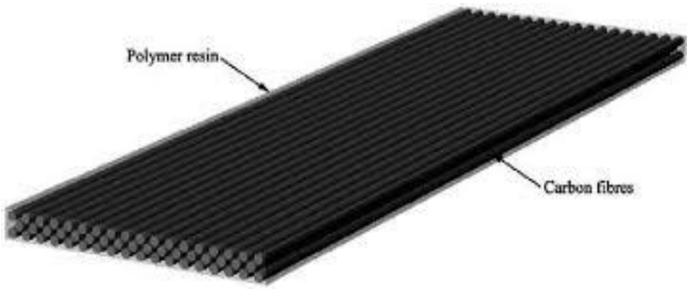


Fig.13 *Typical structure of CFRP*

B. Basalt Fibre Reinforced Polymer (BFRP)

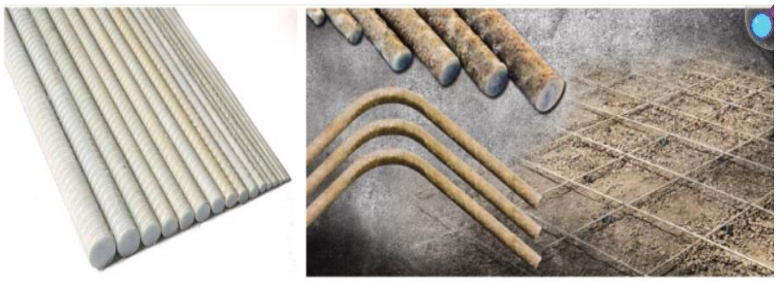
Basalt Fibre Reinforced Polymer (BFRP) is a composite material made of basalt fibres embedded in a polymer matrix, increasingly used in bridge engineering for stay cables and structural reinforcement. BFRP offers high tensile strength (1000–3000 MPa), good corrosion and chemical resistance, and a favourable strength-to-weight ratio compared to steel. In cable-stayed bridges, BFRP cables help reduce dead load, improve durability in marine or humid environments, and resist alkaline and chemical attack. They are also non-magnetic, non-corrosive, and cost-effective.

(a) (b)

Fig.14 *BFRP composites (a) basalt fibre, (b) BFRP bar*

C. *Glass Fibre Reinforced Polymer (GFRP)*

Glass Fibre Reinforced Polymer (GFRP) is a composite material composed of glass fibres embedded in a polymer matrix, used in bridge engineering for stay cables, deck reinforcement, and strengthening works. In cable-stayed bridges, GFRP cables offer good tensile strength (500–1500 MPa), are lightweight, and provide excellent corrosion and moisture resistance, making them suitable for marine and humid environments. They are also economical and easier to fabricate.



(a) (b)

Fig.15 *GFRP tendons (a) Glass bars, (b) Glass mesh*

D. *Aramid Fibre Reinforced Polymer (AFRP)*

Aramid Fibre Reinforced Polymer (AFRP) is a composite material made of aramid fibres (such as Kevlar) embedded in a polymer matrix, used in bridge engineering for stay cables and tension members due to its high tensile strength (2000–3500 MPa) and excellent fatigue and impact resistance. In cable-stayed bridges, AFRP cables are advantageous for their light weight, high toughness,

and good resistance to corrosion and vibration, which enhance bridge durability and dynamic performance. They also maintain stable performance under cyclic loading and have low creep.

(a) Rigid AFRP tendon (b) Flexible AFRP tendon

Fig.16 *AFRP Composites*

E. *Steel tendons*

Steel tendons are the most widely used materials for stay cables and tension members in cable-stayed bridges due to their high tensile strength (typically 1770–2100 MPa), excellent ductility, and reliable long-term performance. They are composed of high-strength steel wires or strands, often galvanized or coated to improve corrosion resistance. In cable-stayed bridges, steel tendons efficiently carry large tensile forces, provide high stiffness, and allow for easy anchorage and adjustability during construction and maintenance. Their advantages include high modulus of elasticity (~200 GPa), proven performance, and cost-effectiveness.

Fig.17 *Steel Tendons*

F. *Steel*

Steel is a traditional and widely used construction material in cable-stayed bridges, employed in stay cables, pylons, girders, and deck components due to its high tensile and compressive strength (up to 250–600 MPa for structural steel) and excellent ductility. It has a high modulus of elasticity (~200 GPa), providing superior stiffness and load-carrying capacity. In cable-stayed bridges, steel ensures efficient force transfer, ease of fabrication, and reliable performance under dynamic and fatigue loading.

Its advantages include high strength, toughness, recyclability, and adaptability to prefabrication.

Fig. 18 Steel

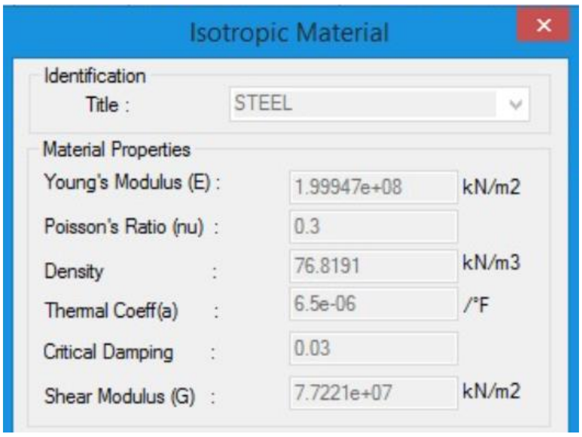


Fig.19 Material Properties dialogue box in StaadPro

Table.1 *Material Properties*

Property	Young's Modulus (kN/m2)	Poisson's Ratio	Density (kN/m3)	Thermal Coeff (/°F)	Critical Damping	Shear Modulus (kN/m2)
Steel	1.99947e+08	0.3	76.8191	6.5e-06	0.03	7.7221e+07
CFRP	1.45e+08	0.28	15.7	2e-06	0.02	5.66e+07
BFRP	8.5e+07	0.28	26	4.44e-06	0.02	3.3465e+07
GFRP	4e+07	0.28	19.62	1e-05	0.02	1.5556e+07
AFRP	7e+07	0.3	13.734	2.78e-06	0.02	2.6923e+07
Steel Tendon	2e+08	0.3	77.005	6.67e-06	0.01	7.6923e+07

7.3 Loads and Load Combinations

7.3.1 Load Parameters

1) Dead Load:
   - Self-weight = 6kN/m

2) Wind Load:
   - IS 875 (Part-3): 2015
   - Exposure Factor = 1

3) Vehicle Load:

- Width = 1.8m

Load (kN)	Distance (m)
10	0
10	2
10	2

4) Seismic Definitions:

- Zone = 0.24
- Response Reduction Factor = 5
- Importance Factor = 1
- Rock and Soil Site Factor =1
- Type of Structure = 1
- Damping Ratio = 0.05
- IS 1893(Part-1): 2016

7.3.2 Load Combinations

1) 1.5 Dead
2) 1.2 Dead + 1.2 Wind (1)
3) 1.2 Dead + 1.2 Wind (2)
4) 1.2 Dead + 1.2 Wind (3)
5) 1.2 Dead + 1.2 Wind (4)
6) 1.2 Dead + -1.2 Wind (1)
7) 1.2 Dead +-1.2 Wind (2)
8) 1.2 Dead +-1.2 Wind (3)
9) 1.2 Dead +-1.2 Wind (4)
10) 1.2 Dead + 1.2 Seismic-H (1)
11) 1.2 Dead + 1.2 Seismic-H (2)
12) 1.2 Dead + 1.2 Seismic-H (3)
13) 1.2 Dead + 1.2 Seismic-H (4)
14) 1.2 Dead + -1.2 Seismic-H (1)
15) 1.2 Dead + -1.2 Seismic-H (2)
16) 1.2 Dead + -1.2 Seismic-H (3)
17) 1.2 Dead + -1.2 Seismic-H (4)
18) 1.5 Dead + 1.5 Wind (1)
19) 1.5 Dead + 1.5 Wind (2)
20) 1.5 Dead + 1.5 Wind (3)
21) 1.5 Dead + 1.5 Wind (4)
22) 1.5 Dead +-1.5 Wind (1)
23) 1.5 Dead +-1.5 Wind (2)
24) 1.5 Dead +-1.5 Wind (3)
25) 1.5 Dead +-1.5 Wind (4)
26) 1.5 Dead + 1.5 Seismic-H (1)
27) 1.5 Dead + 1.5 Seismic-H (2)
28) 1.5 Dead + 1.5 Seismic-H (3)
29) 1.5 Dead + 1.5 Seismic-H (4)

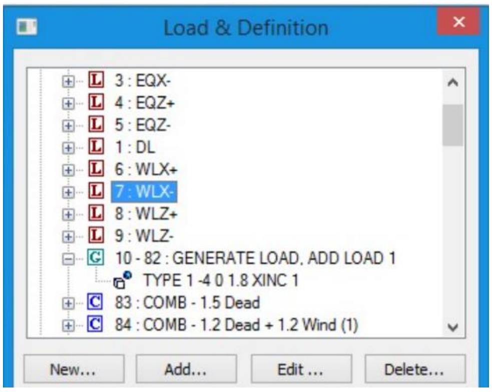


***Fig.20** Load cases*

30) 1.5 Dead +-1.5 Seismic-H (1)
31) 1.5 Dead +-1.5 Seismic-H (2)
32) 1.5 Dead +-1.5 Seismic-H (3)
33) 1.5 Dead +-1.5 Seismic-H (4)
34) 0.9 Dead + 1.5 Wind (1)
35) 0.9 Dead + 1.5 Wind (2)
36) 0.9 Dead + 1.5 Wind (3)
37) 0.9 Dead + 1.5 Wind (4)
38) 0.9 Dead +-1.5 Wind (1)
39) 0.9 Dead +-1.5 Wind (2)
40) 0.9 Dead +-1.5 Wind (3)
41) 0.9 Dead +-1.5 Wind (4)
42) 0.9 Dead + 1.5 Seismic-H (1)
43) 0.9 Dead + 1.5 Seismic-H (2)
44) 0.9 Dead + 1.5 Seismic-H (3)
45) 0.9 Dead + 1.5 Seismic-H (4)
46) 0.9 Dead + -1.5 Seismic-H (1)
47) 0.9 Dead +-1.5 Seismic-H (2)
48) 0.9 Dead + -1.5 Seismic-H (3)
49) 0.9 Dead + -1.5 Seismic-H (4)

where,

- Wind (1) – WLX+
- Wind (2) – WLX-
- Wind (3) – WLZ+
- Wind (4) – WLZ-
- Seismic-H (1) – EQX+
- Seismic-H (2) – EQX-
- Seismic-H (3) – EQZ+
- Seismic-H (4) – EQZ-

8. RESULTS AND DISCUSSION

8.1 Static Load Analysis

Considering beam no. 107

8.1.1 Displacement Results

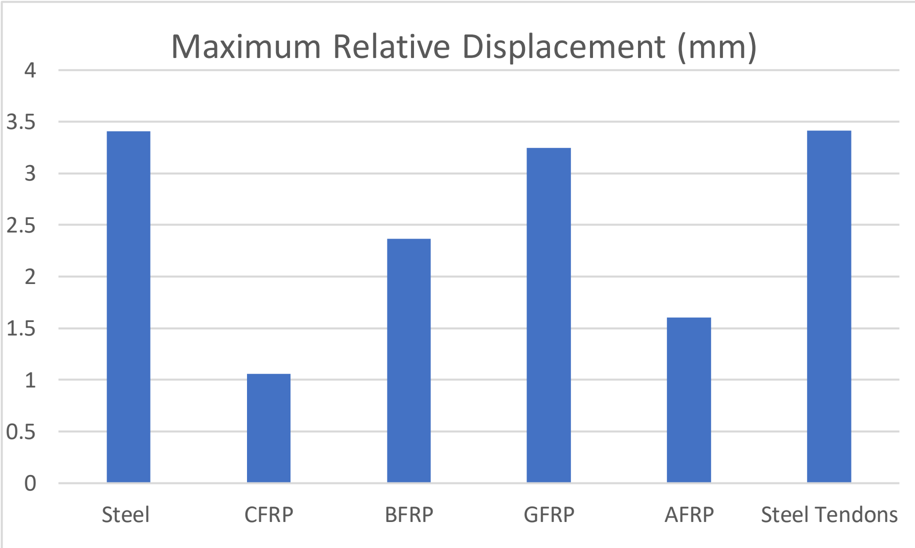


Fig. 21 *Comparison of maximum relative displacements*

The graph shows that **steel tendons and steel** exhibit the highest displacement values, indicating greater flexibility under loading.
CFRP and AFRP record the lowest displacements, showing better stiffness and superior control of deformation compared to the other materials.
Overall, **FRP materials (especially CFRP and AFRP)** significantly reduce displacement, suggesting improved structural performance and serviceability in cable-stayed bridge applications.

8.1.2 Beam Results

A. Axial Forces , Fx (kN)
Considering beam no. 107

Table 2 *Maximum Axial Force, Fx (kN)*

Sl. No.	L/C		AFRP	Steel Tendons	BFRP	CFRP	GFRP	Steel
1	DL	Max +ve	998.86	4071.14	1541.96	1236.78	1047.3	4062.6
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
2	EQX+	Max +ve	31.16	28.01	31.48	29.91	28.74	28.01
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
3	EQX-	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-31.16	-28.01	-31.48	-29.91	-28.74	-28.01
4	EQZ+	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-2.92	-11.79	-4.2	-7.75	-0.61	-11.8

5	EQZ-	Max +ve	2.92	11.79	4.2	7.75	0.61	11.8
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
6	WLX+	Max +ve	0	0	0	0	0	0
		Max -ve	0	0	0	0	0	0
7	WLX-	Max +ve	0	0	0	0	0	0
		Max -ve	0	0	0	0	0	0
8	WLZ+	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-7.36	-19.25	-9.22	-15.12	-3.26	-19.26
9	WLZ-	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-7.36	-19.25	-9.16	-14.98	-3.29	-19.1

The analysis of longitudinal forces demonstrates that the Steel Tendon carries the dominant axial load, recording the highest Fx value of 4071.14 under the dead load, confirming its primary role in providing the necessary axial tension or compression for the cable-stayed system. Among the main structural materials, the BFRP composite exhibits the highest axial force capacity 1541.96 kN while the traditional Steel and GFRP beams show the lowest contribution to the primary axial load path.

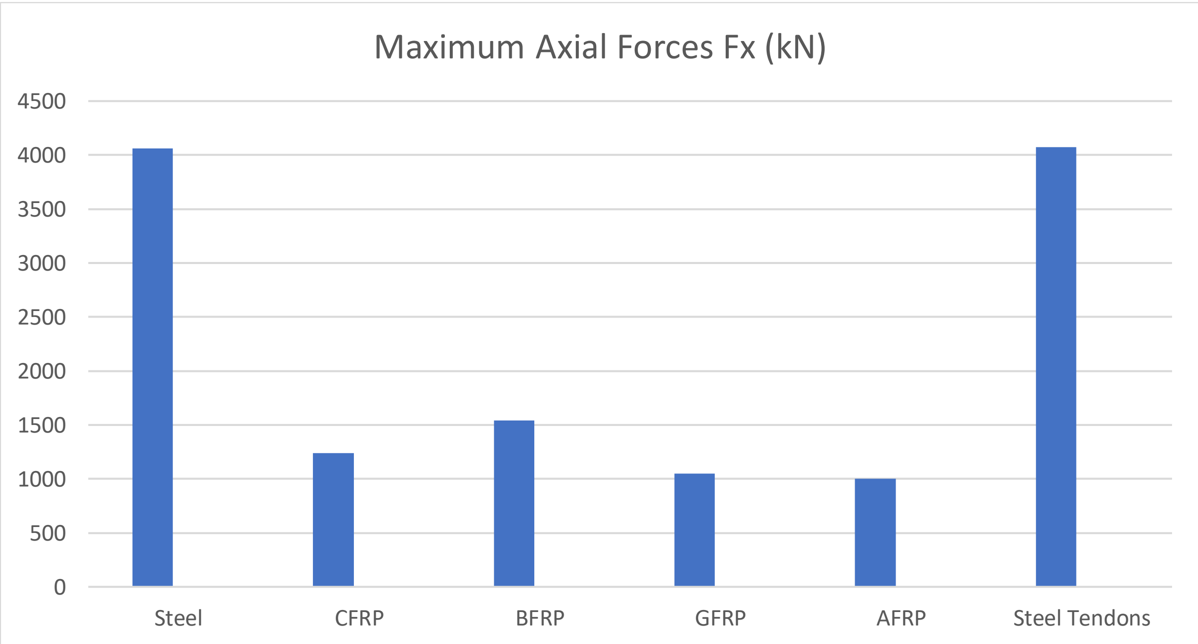


***Fig. 22** Comparison of maximum axial forces*

The graph indicates that **Steel and Steel Tendons carry the highest axial forces**, showing their superior load-carrying capacity compared to other materials.
All **FRP materials (CFRP, BFRP, GFRP, AFRP)** experience significantly lower axial forces, meaning they reduce force demands on the structure due to their lower stiffness and density.
Overall, **the use of FRP cables results in lower axial force transfer**, which can decrease internal stresses in the bridge, but steel and steel tendons remain the most effective when very high axial capacity is required.

B. Shear Forces, Fy (kN)

Table3 *Maximum Shear Force, Fy (kN)*

Sl. No.	L/C		Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
1	DL	Max +ve	562.72	101.92	189.82	118.04	139.83	561.37
		Max -ve	-404.96	-70.67	-136.91	-79.25	-106.72	-403.97
2	EQX+	Max +ve	6.27	3.92	4.35	5.41	2.87	6.27
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
3	EQX-	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-6.27	-3.92	-4.35	-5.41	-2.87	-6.27
4	EQZ+	Max +ve	0.1	N/A	0	0.05	N/A	0.1
		Max -ve	N/A	-0.01	N/A	N/A	-0.02	N/A
5	EQZ-	Max +ve	N/A	0.01	N/A	N/A	0.02	N/A
		Max -ve	-0.1	N/A	0	-0.05	N/A	-0.1
6	WLX+	Max +ve	0	0	0	0	0	0
		Max -ve	0	0	0	0	0	0
7	WLX-	Max +ve	0	0	0	0	0	0
		Max -ve	0	0	0	0	0	0
8	WLZ+	Max +ve	0.19	0.01	0.03	0.11	N/A	0.19
		Max -ve	N/A	N/A	N/A	N/A	-0.01	N/A
9	WLZ-	Max +ve	0.15	N/A	0.01	0.08	N/A	0.15
		Max -ve	N/A	-0.01	N/A	N/A	-0.02	N/A

The analysis of the shear forces reveals a significant range in performance across the tested materials. The largest vertical shear force Fy observed in the Steel Tendon and GFRP beams, both recording similar maximum values of approximately 562 kN under the Dead Load (1 DL). The Steel Tendon also experiences the most demanding horizontal shear, with an Fz of 13.81 kN. Conversely, the CFRP beam registers the lowest overall vertical shear, peaking at only 101.92 kN, suggesting superior shear distribution efficiency or structural interaction for this specific material configuration. The other composite materials, AFRP and BFRP, showed moderate vertical shear values 189.82 kN and 139.83 kN respectively), placing their shear capacity requirements between the GFRP and CFRP materials.

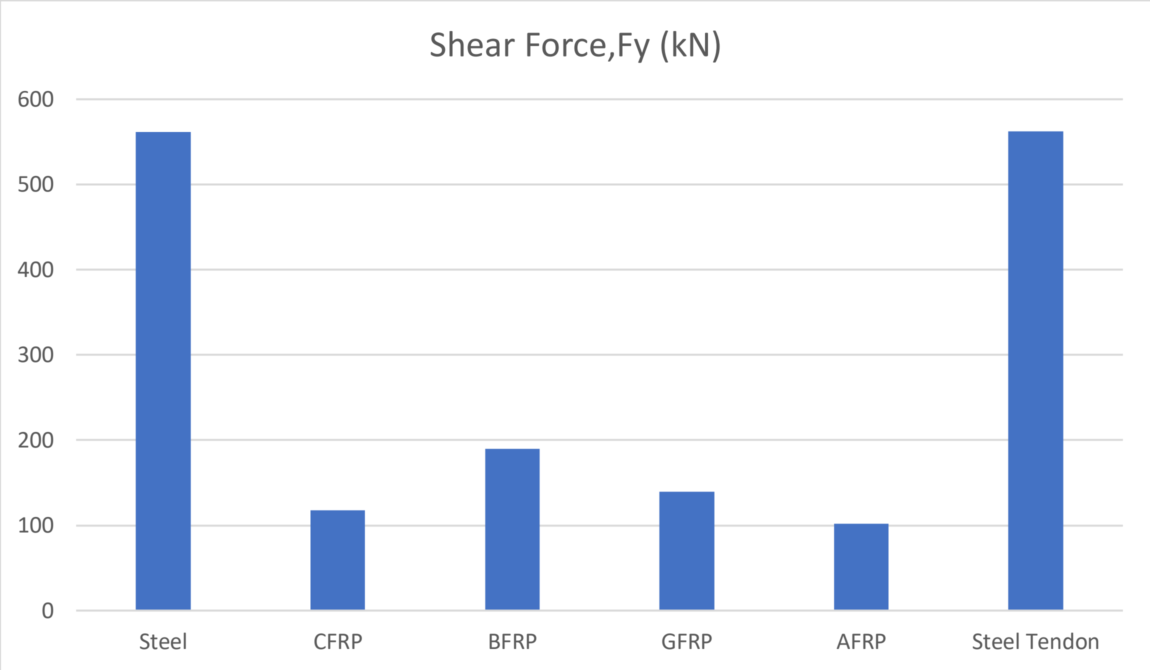


Fig.23 *Comparison of maximum shear force (Fy)*

- Both Steel and Steel Tendon reinforcement deliver overwhelmingly superior ultimate shear capacity (approx. 560 kN) compared to all FRP types in this plane, highlighting a significant difference in performance.

- BFRP demonstrates the highest shear capacity among the FRP reinforcements (approx. 190 kN), while GFRP provides the second highest (approx. 140 kN).

- AFRP and CFRP offer the lowest shear resistance in the Fy direction, with values around 100 kN and 120 kN, respectively.

C. Bending Moment, Mz (kN)

Table 4 *Maximum Bending Moment, Mz (kN-m)*

Sl. No.	L/C		Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
1	DL	Max +ve	1668.44	324.16	598.1	354.15	446.98	1664.47
		Max -ve	-1258.35	-214.09	-388.22	-277.17	-261.78	-1255.37
2	EQX+	Max +ve	31.48	21.14	23.27	28	15.7	31.47
		Max -ve	-80.71	-48.95	-54.5	-68.78	-35.63	-80.7
3	EQX-	Max +ve	80.71	48.95	54.5	68.78	35.63	80.7
		Max -ve	-31.48	-21.14	-23.27	-28	-15.7	-31.47
4	EQZ+	Max +ve	2.23	0.49	0.52	1.26	0.43	2.22
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
5	EQZ-	Max +ve	N/A	N/A	N/A	N/A	N/A	N/A
		Max -ve	-2.23	-0.49	-0.52	-1.26	-0.43	-2.22
6	WLX+	Max +ve	0	0	0	0	0	0

		Max -ve	0	0	0	0	0	0
7	WLX-	Max +ve	0	0	0	0	0	0
		Max -ve	0	0	0	0	0	0
8	WLZ+	Max +ve	3.85	0.92	1.21	2.53	0.56	3.85
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A
9	WLZ-	Max +ve	3.57	0.88	1.03	2.3	0.72	3.57
		Max -ve	N/A	N/A	N/A	N/A	N/A	N/A

Mz Bending Moments the Steel Tendon and steel cases result in the highest maximum Mz bending moments 1668 kN m positive and -1258kN m under Dead Load (DL).In contrast, the AFRP, BFRP, CFRP, and GFRP cases show significantly lower Mz demands, with the lowest positive moment being 324.16 kN m. This data indicates that the structural system using the Steel Tendon and Steel experiences a substantially greater flexural demand than the other FRP systems under the same DL conditions.

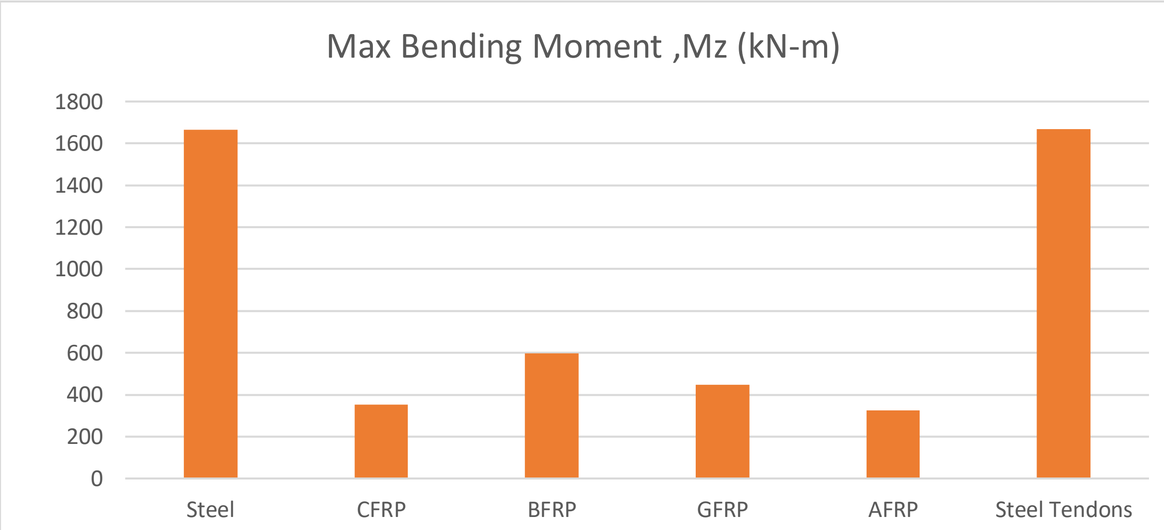


Fig. 24 *Comparison of maximum bending moment (Mz)*

This comparative trend indicates that steel tendons provide the most efficient structural response in terms of moment control, while FRP-based tendons though advantageous in corrosion resistance and weight reduction result in slightly increased internal forces. Therefore, the choice of tendon material must balance mechanical performance with durability and maintenance considerations, depending on the bridge's design priorities.

8.1.3 Support Reactions

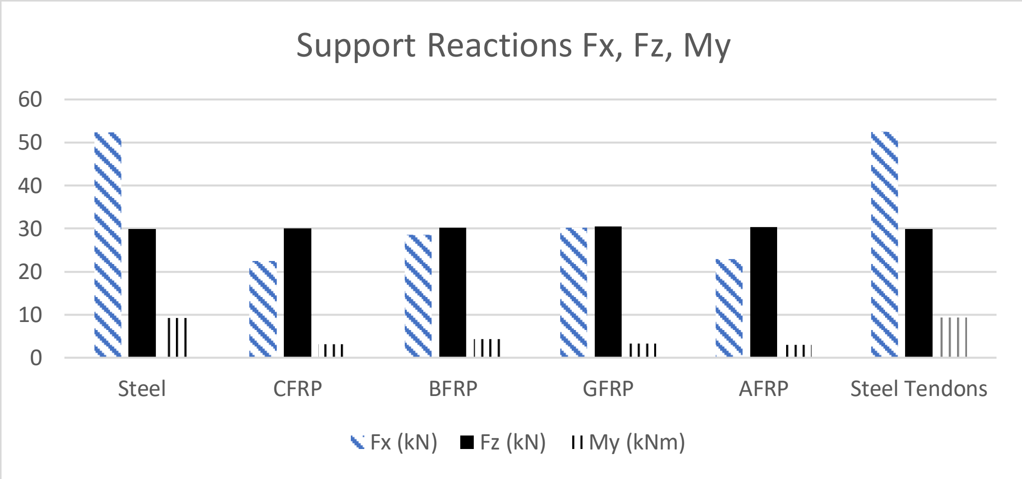


Fig. 25 *Comparison of support reactions (Fx, Fz, My)*

The key finding from the support reaction analysis is the clear distinction between Steel/Steel Tendon and FRP reinforcements. The Vertical Force Fz remained constant across all materials around 30-kN, indicating a consistent vertical load. However, both Steel and Steel Tendons produced significantly higher Axial Forces Fx 52 kN and Moment Reactions My 9-9.5 kNm compared to the FRP materials (where Fx was 22-30 kN and My was <4 kNm). This suggests that the Steel and Steel Tendon reinforcements introduced substantially greater horizontal and rotational forces at the supports due to their different structural stiffness or boundary conditions, while the FRP materials exhibited a more flexible behaviour at the supports.

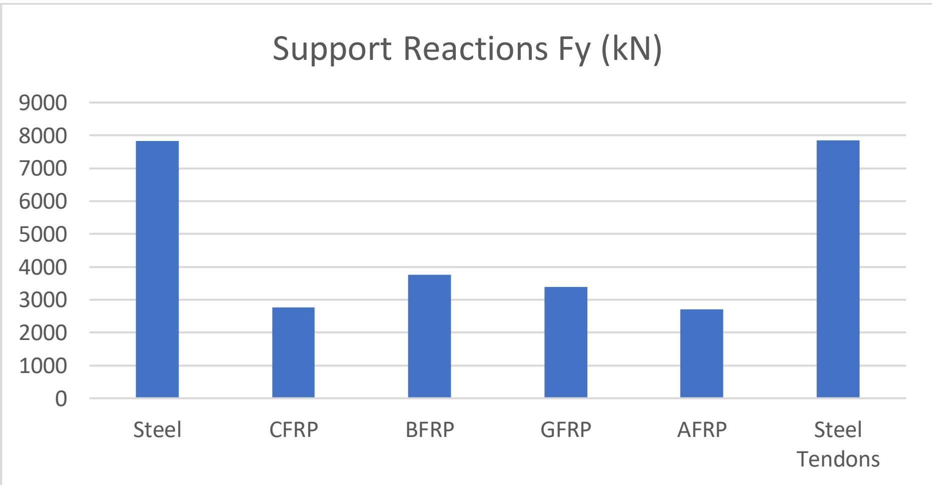


Fig. 26 *Comparison of support reactions (Fy)*

This strong divergence indicates that the vertical load transfer mechanism or the stiffness/flexibility characteristics under the applied loading (which is likely vertical) are fundamentally different between the high-stiffness steel reinforcements and the composite FRP reinforcements. The high Fy values for Steel and Steel Tendons suggest that these systems attract or withstand significantly more vertical force at the support compared to the FRP systems.

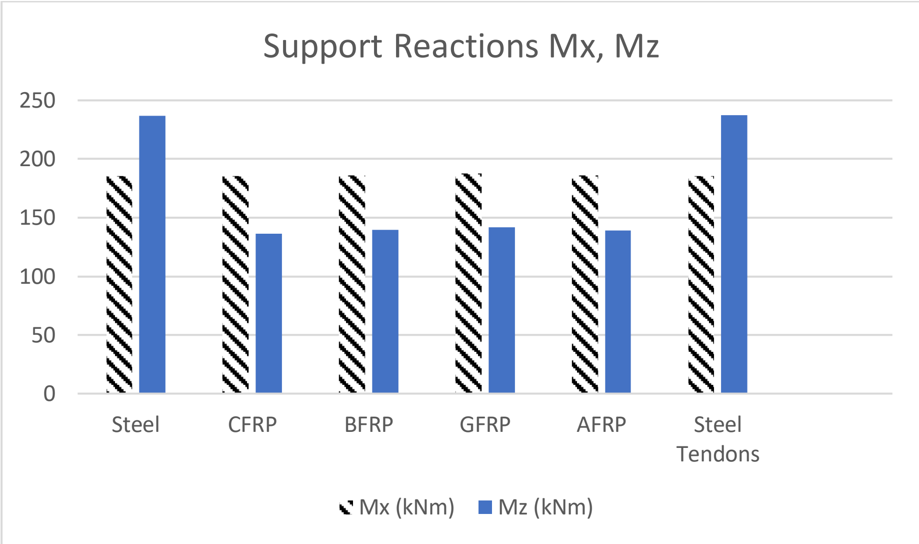


Fig. 27 Comparison of support reactions (Mx, Mz)

The use of Steel and Steel Tendons results in an Mz support reaction that is approximately 65% higher than the moment generated by the FRP composites. This indicates that while the torsional restraint Mx is unaffected, the out-of-plane rotational restraint provided by the supports is significantly greater for the Steel/Steel Tendon reinforced systems.

8.1.4 Plate Center Stress Results

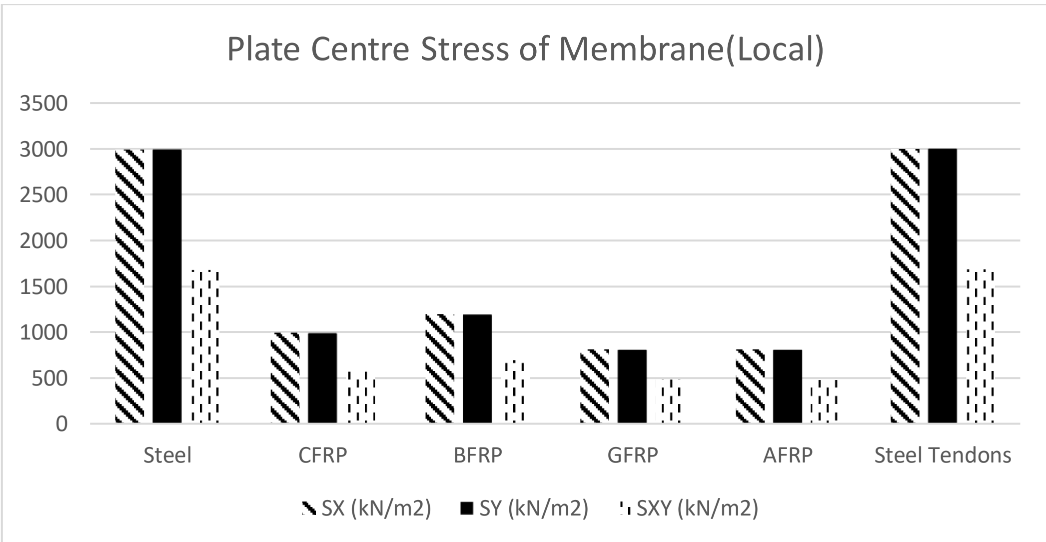


Fig.28 *Comparison of plate center stresses*

The Steel and Steel Tendon reinforcements experience local plate centre stresses (both normal and shear) that are 2.6 to 3.7 times higher than those developed in the FRP-reinforced sections. This demonstrates that the high-stiffness metallic reinforcements transfer significantly larger local stress concentrations to the surrounding membrane elements compared to the more flexible FRP composites.

8.2 Vehicle Loads Analysis

8.2.1 Displacement Results

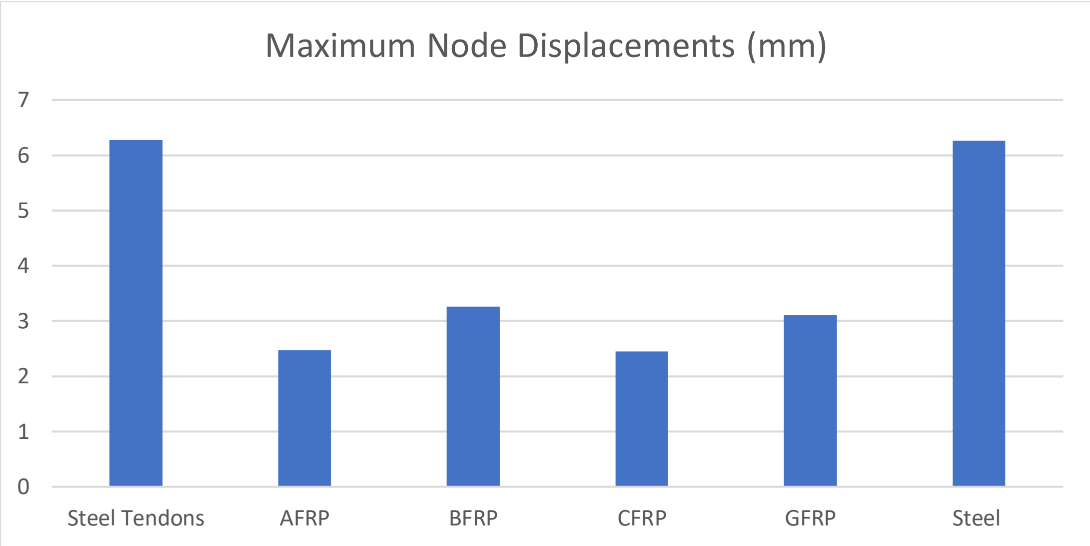


Fig. 29 *Comparison of max node displacements*

The displacement comparison shows that the choice of cable material has a clear influence on the overall response of the cable-stayed bridge under vehicular loading. Steel tendons recorded the highest displacements, indicating relatively lower stiffness efficiency for service-level performance. In contrast, AFRP and CFRP cables produced the smallest displacements, reflecting their superior stiffness and better control of deck movements. BFRP and GFRP showed moderate behaviour, performing better than steel but not as effectively as aramid- or carbon-based cables. Overall, the results suggest that AFRP and CFRP are the most effective substitutes for steel cables in enhancing displacement performance and improving bridge serviceability.

8.2.2 Beam Results

Table 5 *Beam End Forces summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max Fx (kN)	7878.87	2747.96	3793.2	2797.37	3417.83	7863.43
Min Fx (kN)	-2718.71	-708.14	-1049.4	-862.09	-755.61	-2713.1
Max Fy (kN)	679.3	229.16	334.78	225.08	281.69	677.93
Min Fy (kN)	-679.34	-275.87	-345.48	-264.06	-324.35	-677.96
Max Fz (kN)	145.8	34.58	52.73	45.79	33.35	145.51
Min Fz (kN)	-145.8	-34.58	-52.73	-45.79	-33.35	-145.51
Max Mx (kN-m)	58.23	21.92	32.13	20.57	38.5	58.11
Min Mx (kN-m)	-58.23	-21.92	-32.13	-20.57	-38.5	-58.1
Max My (kN-m)	261.97	68.5	98.95	82.67	74.41	261.44
Min My (kN-m)	-261.97	-68.52	-98.95	-82.68	-74.56	-261.44
Max Mz (kN-m)	1792.04	397.83	603.9	383.67	529.85	1787.78
Min Mz (kN-m)	-585.66	-215.78	-245.65	-201.92	-261.7	-584.38

The beam end force comparison shows that steel tendons and structural steel generate the highest axial forces (Fx) in both tension and compression, indicating a stiffer and more force-demanding response when steel is used as the cable material. In contrast, all FRP alternatives—AFRP, BFRP, CFRP, and GFRP—produce significantly lower axial forces, reflecting their lower density and different elastic behaviour, which reduces the load transmitted to the supporting beams. BFRP and GFRP carry moderately higher forces than AFRP and CFRP, but still remain well below steel.

The shear forces (Fy, Fz) and bending moments (Mx, My, Mz) follow a similar trend, with steel exhibiting the largest values, while FRP materials result in substantially reduced beam actions, indicating a lighter and more flexible structural response. Overall, FRP cable substitutions reduce beam force demand and improve force distribution across the bridge, particularly when using AFRP and CFRP, which show the most balanced behaviour.

8.2.3 Support Reactions

Table 6 *Support Reactions summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max Fx (kN)	52.72	20.19	28.95	16.97	30.86	52.61
Min Fx (kN)	-52.72	-20.19	-28.95	-16.97	-30.86	-52.61
Max Fy (kN)	7878.87	2747.96	3793.2	2797.37	3417.83	7863.43
Min Fy (kN)	2758.94	953.24	1278.2	1063.45	1025.69	2753.81
Max Fz (kN)	9.59	8.59	8.99	8.23	9.32	9.58
Min Fz (kN)	-9.53	-8.47	-8.88	-8.1	-9.23	-9.53
Max Mx (kN-m)	38.48	34.55	36.09	33.26	37.41	38.46
Min Mx (kN-m)	-37.39	-33.11	-34.75	-31.62	-36.15	-37.36
Max My (kN-m)	9.41	3.07	4.45	3.23	3.36	9.39
Min My (kN-m)	-9.41	-3.07	-4.45	-3.23	-3.36	-9.39
Max Mz (kN-m)	238.09	86	124.56	75.65	127.47	237.6
Min Mz (kN-m)	-238.09	-86	-124.56	-75.65	-127.47	-237.6

The support reactions show that steel tendons and structural steel produce the highest forces and moments at the supports, reflecting their higher stiffness and greater load transfer. All FRP cable options generate significantly lower reaction forces, with AFRP and CFRP giving the smallest values. This indicates that FRP cables reduce the load and moment demands on the supports, leading to a lighter and more flexible overall structural response. Overall, AFRP and CFRP offer the most efficient reduction in support reactions compared to steel.

8.2.4 Plate Center Stresses

***Table** 7 Plate center stresses summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max SX (kN/m2)	1989.43	527.7	786.52	650.42	549.88	1985.4
Min SX (kN/m2)	22.38	-41.37	-21.39	-13.87	-132.5	22.28
Max SY (kN/m2)	1968.25	507.32	765.84	628	530.93	1964.22
Min SY (kN/m2)	21.68	-41.42	-21.73	-14.18	-129.85	21.58
Max SXY (kN/m2)	1090.33	281.11	426.39	344.29	284.99	1088.08
Min SXY (kN/m2)	-1090.33	-281.11	-426.39	-344.29	-284.99	-1088.08

The plate stress results indicate that the choice of cable material directly affects how vehicle loads are transferred into the deck plates. Steel cables produce the highest SX, SY, and SXY stresses, reflecting their higher stiffness and the larger forces they transmit to the deck. In contrast, all FRP cable options—AFRP, BFRP, CFRP, and GFRP—result in substantially lower plate stresses, showing that FRP cables reduce load concentration and lead to a more moderate stress distribution. Among these, CFRP and AFRP provide the greatest reduction, indicating better structural efficiency in limiting deck plate stresses under vehicle loading.

8.3 Seismic Analysis

Considering all the combined loads according to IS 456 2015

8.3.1 Displacement Results

The combined load displacement results show that the choice of cable material has a direct influence on the global dynamic response of the cable-stayed bridge. Steel cables and tendons exhibit the highest maximum node displacements, indicating a stiffer but more force-intensive response that amplifies overall movements during seismic and wind loading. All FRP alternatives—AFRP, BFRP, CFRP, and GFRP—demonstrate noticeably lower displacements, reflecting their lower mass and different elastic characteristics, which help reduce inertial effects under earthquake excitation. CFRP and AFRP, in particular, provide the most stable displacement behaviour, suggesting improved damping characteristics and better control of deck and tower movements under multi-hazard load combinations.

Overall, the results indicate that FRP cable materials can enhance seismic performance by reducing structural displacements, with CFRP and AFRP showing the most favourable behaviour compared to conventional steel cables.

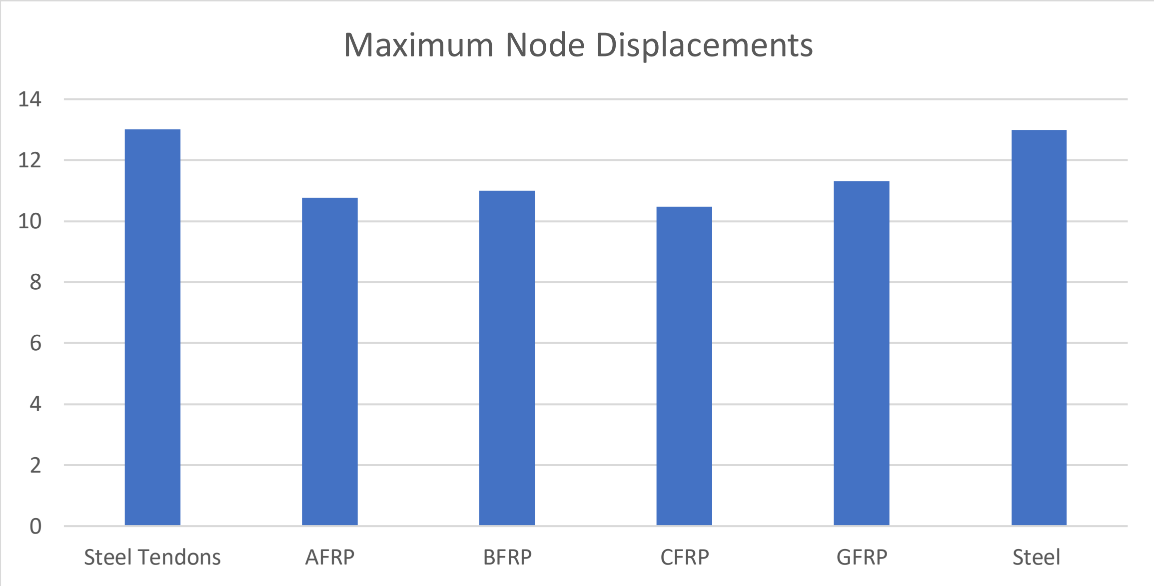


Fig. 30 *Comparison of max node displacements*

8.3.2 Beam Results

Table 8 *Beam End Forces summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max Fx (kN)	1194.96	4252.05	5820.3	4327.04	5254.97	11925.99
Min Fx (kN)	-4085.7	-1057.28	-1589.2	-1303.06	-1115.18	-4077.28
Max Fy (kN)	1015.32	355.15	512.37	339.76	434.78	1013.25
Min Fy (kN)	-1015.37	-402.47	-512.39	-384.78	-474.21	-1013.31
Max Fz (kN)	220.08	56.88	79.55	69.15	57.95	219.63
Min Fz (kN)	-220.08	-57.28	-79.55	-69.15	-58.33	-219.63
Max Mx (kN-m)	89.89	56.74	64.9	45.24	72.25	89.72
Min Mx (kN-m)	-89.89	-56.74	-64.9	-45.24	-72.25	-89.72
Max My (kN-m)	392.97	357.46	363.04	356.24	365	392.18
Min My (kN-m)	-392.97	-355.81	-361.52	-354.7	-363.39	-392.18
Max Mz (kN-m)	2744.78	623.34	933.15	623.25	826.43	2738.38
Min Mz (kN-m)	-932.22	-405.94	509.83	-372.76	-528.48	-930.29

The above table compares beam end forces under combined seismic, wind, and dead loads. The results clearly indicate that Steel Tendons impose the highest structural demand, generating a maximum axial force Fx of 11,926 kN and a bending moment Mz of 2,738 kN-m.

In contrast, substituting steel with composite cables drastically reduces these forces due to the lower mass of FRP materials. AFRP and CFRP proved most effective, lowering the maximum bending moment to approximately 623 kN-m—a reduction of nearly 77%. This significant decrease in internal forces confirms that using lightweight FRP cables minimizes inertial loads, thereby enhancing the bridge's seismic performance.

8.3.3 Support Reactions

Table 9 *Support Reactions summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max Fx (kN)	112.05	60.62	74.28	56.75	75.93	111.88
Min Fx (kN)	-112.05	-60.62	-74.28	-56.75	-75.93	-118.88
Max Fy (kN)	11949.16	4252.05	5820.3	4327.04	5254.97	11925.99
Min Fy (kN)	2411.9	788.89	1080.9	886.66	854.96	2407.28
Max Fz (kN)	59.`13	57.28	57.92	56.98	58.33	59.13
Min Fz (kN)	-58.88	-56.88	-57.55	-56.59	-57.95	-58.87
Max Mx (kN-m)	335.17	329.85	332.02	327.5	334.92	335.14
Min Mx (kN-m)	-333.08	-326.75	-329.1	-324.39	-332.01	-333.05
Max My (kN-m)	15.72	6.68	8.67	6.59	7.34	15.69
Min My (kN-m)	-15.72	-6.68	-8.67	-6.59	-7.34	-15.69
Max Mz (kN-m)	560.64	321.53	381.59	308.19	382.69	559.87
Min Mz (kN-m)	-560.64	-321.53	-381.59	-308.19	-382.69	-559.87

Steel Tendons generated the highest foundation demand, recording a maximum vertical reaction Fy of 11,949 kN and a peak moment Mz of 560 kNm. Conversely, the use of CFRP and AFRP cables significantly mitigated these loads. The maximum vertical reaction for CFRP dropped to 4,327 kN—a reduction of approximately 64% compared to steel. Similarly, the supporting moments Mz were reduced by roughly 45% (down to 308 kNm).

In a seismic context, this reduction is critical. The use of lightweight FRP cables drastically lowers the total mass of the structure, thereby reducing the inertial forces transferred to the substructure during ground motion. This suggests that FRP cables can lead to smaller, more economical foundation designs while improving overall seismic safety.

8.3.4 Plate Center Stresses

Table 10 *Plate center stresses summary*

	Steel Tendons	AFRP	BFRP	CFRP	GFRP	Steel
Max SX (kN/m2)	3001.32	811.83	1199.4	993.63	812.54	2995.29
Min SX (kN/m2)	-1.39	-65.07	-52.78	-41.83	-197.12	-1.48
Max SY (kN/m2)	2996.1	804.85	1192.7	985.88	805.44	2990.06
Min SY (kN/m2)	-2.04	-72.36	-52.9	-42.02	-203.38	-2.12
Max SXY (kN/m2)	1683.63	475.72	692.58	566.45	484.14	1680.26
Min SXY (kN/m2)	-1683.63	-475.72	-692.58	-566.45	-484.14	-1680.26

The Steel Tendons configuration resulted in the highest demand, subjecting the deck plate to peak longitudinal and transverse stresses Max SX and Max SY of approximately 3,000 kN/m.In contrast, using AFRP or GFRP cables reduced these stresses to approximately 812 kN/m

This reduction of over 70 is crucial for bridge resilience. By minimizing the high stress concentrations associated with inertial forces, the deck plate experiences less localized strain. This directly improves the deck's resistance to fatigue damage and cracking under dynamic loading, allowing for a potentially more slender and robust deck design, which is advantageous in seismic zones

8.4 Material Efficiency Analysis

The efficiency of stay-cable materials directly influences the global performance, durability, and dynamic behaviour of a cable-stayed bridge. In this study, six materials—Steel Tendons, Structural Steel, CFRP, AFRP, BFRP, and GFRP—were evaluated to understand their relative efficiency in terms of displacement control, force transfer, support reaction demand, and stress distribution under combined dead load, vehicle load, wind loading, and earthquake actions.

(a) Displacement Performance

The maximum node displacement results show that steel cables and tendons produce the highest deck and pylon movements, owing to their higher mass and greater force transfer during seismic and wind excitation. In contrast, FRP materials exhibit noticeably reduced displacements, with CFRP and AFRP performing the best. Their superior strength-to-weight ratio and lower mass help minimise inertial effects, making them more efficient under dynamic loads.

(b) Force Transfer to Deck Members

Beam end force analysis indicates that steel systems introduce the largest axial forces, shear forces, and bending moments into the deck and tower. FRP cables significantly reduce these demands, demonstrating smoother load flow and lower localised stresses. Among the FRPs, AFRP, CFRP, and BFRP show the most favourable reductions, supporting improved fatigue life and reduced overstress risk.

(c) Support Reaction Efficiency

Support reactions further confirm that steel cables generate the highest vertical and lateral reaction forces, increasing the load demand on foundations and anchor zones. FRP cables—particularly CFRP and AFRP—reduce these reactions across all axes, lowering base shear and overturning moments, which is advantageous for seismic resilience and foundation optimisation.

(d) Plate Stress Response

Plate centre stress results reveal that steel induces the highest SX, SY, and SXY stresses within the deck plates due to its stiffness and heavier mass. All FRP materials provide reduced stress levels, with CFRP and AFRP offering the greatest reductions. Lower plate stresses correspond to improved fatigue performance and reduced crack initiation risks.

(e) Overall Material Efficiency Outlook

When considering stiffness-to-weight ratio, displacement behaviour, seismic performance, stress distribution, and long-term durability, the materials rank as follows:

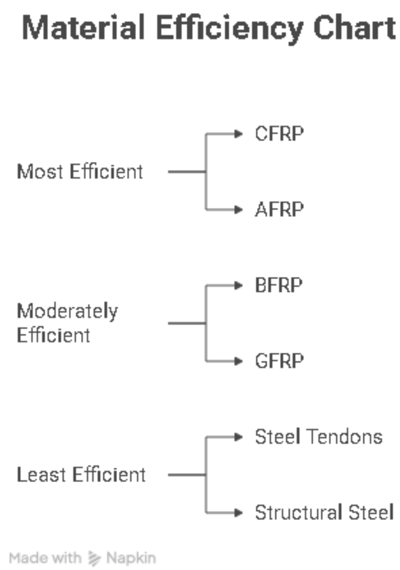


Fig.30 *Comparison of max node displacements*

In summary, FRP cables—especially CFRP and AFRP—demonstrate superior efficiency for modern cable-stayed bridges, offering reduced displacements, lower force transmission, enhanced seismic behaviour, and improved durability compared to traditional steel cable systems.

8.5 Cost Comparative Analysis

Cost performance is a key factor in the selection of stay-cable materials for a cable-stayed bridge, as it influences both the initial project budget and the long-term economic sustainability of the structure. This sub-chapter compares the cost efficiency of Steel, Steel Tendons, CFRP, AFRP, BFRP, and GFRP cables, integrating industry-level cost behaviour with the performance trends observed in the structural analysis of the bridge.

(a) Initial Cost Behaviour

The initial procurement cost varies widely based on material production complexity and global availability:

- Steel & Steel Tendons – Lowest initial cost
  Mass-produced, readily available, and cheapest to install.
- GFRP & BFRP – Low to moderate initial cost
  Economical composite options; cheaper than advanced FRPs.
- AFRP – High initial cost
  Costlier manufacturing, but offers strong performance advantages.
- CFRP – Highest initial cost
  Premium material with complex fabrication and highest per-metre cost.

Initial Cost Ranking:
Steel < GFRP < BFRP < AFRP < CFRP

(b) Maintenance & Replacement Costs

Long-term costs depend heavily on durability and corrosion behaviour:

- Steel – High maintenance burden
  Requires frequent inspection, corrosion protection, retensioning, and periodic replacement.
- FRP Materials – Minimal maintenance
  Corrosion-proof and fatigue-resistant, eliminating expensive protective systems.
- CFRP & AFRP – Lowest lifetime intervention
  Excellent environmental resistance and fatigue performance reduce the need for long-term repair.

Maintenance Cost Ranking:
Steel >> GFRP ≈ BFRP > AFRP > CFRP

(c) Lifecycle Cost (50–100 Years)

When analysed over a full design life:

- Steel experiences the highest lifecycle cost, despite its low initial price, due to corrosion-related rehabilitation and recurrent maintenance.
- GFRP and BFRP have moderate lifecycle costs, providing decent long-term value with limited maintenance.
- CFRP and AFRP demonstrate the lowest lifecycle cost, as their high durability and near-zero corrosion risk reduce long-term expenditure significantly.

Lifecycle Cost Ranking:
Steel > GFRP ≈ BFRP > AFRP > CFRP

(d) Cost vs. Structural Performance Insight

The structural results show:

- Steel produced the highest displacements, stresses, and reactions, increasing structural demand and long-term maintenance.
- FRP cables (especially CFRP & AFRP) reduced displacements and stress concentrations, improving seismic performance and decreasing the likelihood of long-term structural deterioration.

When cost and performance are combined:

- CFRP gives the best overall value (high cost upfront, but highest structural and lifecycle efficiency).
- AFRP is close behind, balancing performance and long-term cost.
- BFRP & GFRP provide cost-friendly alternatives for projects with budget constraints.
- Steel is cost-effective only initially, but becomes expensive across the lifespan of the bridge.

Considering initial investment, maintenance intensity, lifecycle costs, and the performance results from the bridge analysis, CFRP and AFRP emerge as the most cost-efficient cable materials for long-span cable-stayed bridges. Their superior durability, low mass, minimal maintenance, and extended service life create long-term economic advantages. GFRP and BFRP offer moderate cost efficiency, while steel remains the least economical over time despite its low initial cost, due to high maintenance and replacement requirements.

9. CONCLUSION

a. The primary objective of this project was to conduct a comparative structural analysis of a cable-stayed bridge utilizing four types of Fiber Reinforced Polymer (FRP) stay cables (AFRP, BFRP, CFRP, GFRP) against conventional Steel Tendons, specifically evaluating their performance under combined dead, wind, and severe earthquake loads. The findings conclusively demonstrate the technical and economic superiority of lightweight composite cables in enhancing the bridge's resilience and longevity.

b. The detailed analysis of beam end forces, support reactions, and deck plate stresses consistently highlighted the critical role of cable mass in mitigating inertial forces:
   - FRP cables, particularly CFRP and AFRP, drastically reduced the structural demand on the main bridge elements. The maximum bending moment Mz in the girder was reduced by approximately 77% (from 2,738 kNm in Steel to 623 kNm in FRP), while axial forces were cut by approx 64%.
   - The reduced mass translated directly to lower foundation demands. The critical vertical reaction Fy was lowered by approximately 64% (from 11,949 kN in Steel to 4,327 kN in CFRP). This significant reduction improves seismic safety margins and allows for more optimized substructure design.
   - FRP cables reduced localized stress concentrations Max SX/SY by over 70%. This ensures greater fatigue life for the deck plate, reducing the risk of premature cracking and maintenance requirements under dynamic loading conditions.

c. While steel remains the lowest initial cost option, the project’s lifecycle cost analysis shows it is the least economical material over the bridge’s service life due to high maintenance, corrosion risk, and replacement frequency.
   Conversely, CFRP and AFRP offer the best long-term value proposition. Their superior durability, high structural efficiency, minimal need for maintenance, and extended service life justify the higher initial investment. By dramatically reducing critical forces, these materials inherently mitigate structural risk, decrease the likelihood of major post-seismic repair, and simplify future maintenance procedures.

Final Recommendation

Based on the quantitative results—showing optimal performance in reducing seismic forces, foundation loads, and plate stresses—**CFRP** and **AFRP** are the recommended materials for the stay-cable system. They offer a comprehensive solution that maximizes structural safety, minimizes lifecycle costs, and ensures the long-term resilience of the cable-stayed bridge structure, particularly in seismically active regions.

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