Performance Investigation of Carbon Fiber Reinforced Polymer Cable Stayed Bridge

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Abstract:* *The innovative use of Carbon Fiber Reinforced Polymer (CFRP) materials in cable-stayed bridge construction presents a promising alternative to traditional steel cables, offering significant benefits in terms of strength-to-weight ratio, corrosion resistance, and long-term durability. This study investigates the performance characteristics of CFRP cable-stayed bridges through a comprehensive analysis encompassing material properties, structural behavior, and long-term performance under various loading conditions. A series of numerical simulations and experimental tests were conducted to evaluate the mechanical properties and performance metrics of CFRP cables. The research focuses on critical aspects such as tensile strength, fatigue resistance, and the impact of environmental factors on material degradation. The study also includes a comparative analysis with traditional steel cables, highlighting the advantages and potential challenges associated with the adoption of CFRP in bridge engineering. The results demonstrate that CFRP cables exhibit superior performance in terms of weight reduction and resistance to environmental corrosion, which can significantly enhance the lifespan and reduce the maintenance costs of cable-stayed bridges. However, the study also identifies potential challenges, including higher initial material costs and the need for specialized installation techniques. Overall, this research underscores the viability of CFRP as a sustainable and efficient material for modern cable-stayed bridges, providing valuable insights for engineers and decision-makers in the field of bridge construction and maintenance.

***Key Words*: Carbon fiber reinforced polymer, cable stayed bridge, CFC cable, cable configuration, Unknown load Factor**

1.INTRODUCTION

Cable stayed bridges are common types of bridge in which bridge deck is sup- ported by the cables. Usually, such cables are of steel which is having group of strands the reason of Modern cable-stayed bridges are very popular among bridges for four reasons: 1) their visually pleasing design; 2) their efficient and complete use of structural materials; 3) their quick and easy building process; and 4) the bridge's components' comparatively small sizes. The bridge's deck is provided with support by carbon fiber reinforced polymer (CFRP) cables. Because of its distinctive characteristics, carbon fiber-reinforced polymer (CFRP) cables are being considered growing in popularity for use in long-span cable-stayed bridges. A composite material is carbon fiber-reinforced polymer. Composite material is made up of two or more different materials bonded together. Pitch-based carbon fibers and epoxy resin are combined to create carbon fiber reinforced polymer, or CFRP. 65 percent of the volume is made up of fiber, while 35 percent is made up of resin.[1]. The cable profile was employed in the cable stayed bridge's construction to support the deck. Generally, it is Harp pattern, Fan pattern and Semi-Harp pattern. This cable profiles are important while considering lateral load. Reinforced with Carbon Fiber Instead of using steel cables as a stay cable to hold the bridge deck, polymer cable is a sophisticated composite material. Because of its excellent fatigue resistance, low weight, great strength, and lack of corrosion. The material specifications of Carbon Fiber Reinforced Polymer (CFRP) cables vary significantly due to the production process employed by different manufacturers. As compared to steel cable, the tensile strength is higher. A carbon fiber reinforced polymer cable's temperate deformation is just 1/20 that of steel cables. The unit weight is 1/5 that of steel cable. Finite element analysis was then used to examine their structural performance, both in a static and dynamic state. A model for the study and design of the static and dynamic properties of a long span cable stayed bridge using carbon fiber reinforced polymer (CFRP) cables is established using MIDAS Civil. Cable stayed bridge models consist of main span 600 m with H shaped pylon. Fan type cable profile considered having 21 number of cables. For vibration, it can be found that damping increases with vibration amplitude and this is more obvious for steel cable than Carbon Fiber Reinforced Polymer (CFRP) cable. Therefore, compared to steel cables, carbon fiber reinforced polymer (CFRP) cables have a lower vibration amplitude. CFRP cables perform better than steel cables in a few critical mechanical domains, such as creep and relaxation. These flexible constructions' dynamic and aerodynamic responses may be significantly impacted by the introduction of Carbon Fiber Reinforced Polymer (CFRP) cables.

CFRP Cables

Carbon fiber leads embedded in polymer resin composed of Carbon Fiber Reinforced Polymer (CFRP) cable. The first application of carbon fiber reinforced polymer (CFRP) was in 1991 to reinforce the Ibach Bridge in Lucerne, Switzerland [4]. Since 1991, CFRP materials have been employed as cables in cable structures in addition to strengthening, repairing, reinforcing, and prestressing. CFRP cables are typically made from CFRP materials. as shown in table.1. The CFRP cables mechanical properties such as tensile strength (σ), Modules of Elasticity (E) is higher and Density (ρ) smaller as compared to conventional steel cable [4]. Thermoplastic and thermosetting resins are the two primary types of Polymer resin used in CFRP. Compared to steel cables, CFRP cables are lighter, stronger, and more resistant to fatigue and corrosion. They also expand less thermally. During relaxation, CFRP cables experience remarkably minimal stress. The impact of CFRP cables on the mechanical properties of long-span cable-stayed bridges has not yet been the subject of a thorough investigation. In terms of material, element, and structural properties, A steel cable-stayed bridge and a CFRP cable-stayed bridge are compared.

Table -1: A mechanical property of CFRP and steel cable

Cable Name	Type of cable	Density (Kg/M3)	Tensile Strength (GPa)	Elastic Modulus (GPa)
Mitsubisi Lead Line	Parallel CFRP Deform Rod	1600	2.30	147
Tokyo Rope CFCC	Twisted CFRP Round Wire	1500	2.10	137
Steel Full Locked Coil Rope	Twisted Steel Wire	7850	1.50	160

Figure.1 shows the composite core of CFRP cable while manufacturing at factory. With multi strands cable having different diameter. The Tokyo Rope International company is a leading manufacturer of CFCC (Carbon Fiber composite cable) cables. This company have used CFC cables as stay cables in most of the cable stayed bridges. These cables are produced using a large quantity of small-diameter wires. Such wires are also called strands having diameter 5 mm to 20 mm as per The Tokyo Rope International company.

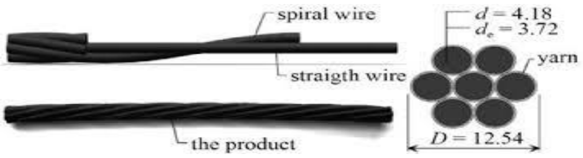

Fig. -1: Composite Core of CFRP cable

3 Overview of CFRP cable stayed Bridge

There are several instances of carbon fiber reinforced polymer cable stayed bridges across the world. The Stork Bridge, which spans a railroad station' s eighteen tracks in Winterthur, Switzerland, was constructed in 1996. It is held up by the main A-frame tower. Two span of nearly equal span 63 m and 61m eighter side of supporting tower. The bridge deck has two principle longitudinal girders at 8 m spaced. These girders support Reinforced concrete slabs. CFRP cables are used two support the deck consists of 241 wires which has 5 mm dia. On each wire. The cables' remarkable strength and resilience were demonstrated when they were subjected to a weight three times higher than what is typically acceptable for the bridge. Over ten million load cycles were endured by the cables, which replicated extended use and the consequences of continuous strain over time. Modern glass fiber-optic sensors and conventional sensors have been installed by the EMPA on the two CFRP cables with their anchoring and the nearby steel cables. These sensors enable continuous monitoring for the detection of stress and deformation. It is also possible to compare the reality of a practical application with theoretical modeling thanks to this arrangement.[5]

4 Methodology

4.1 The Cable Stayed Bridge' s configuration The total span of Bridge which is modelled for 600 m. Main span is considered 300 m. For the calculation of length of side span, the ratio of side span to main span varies from 0.20 to 0.50. So, the length of side span will be 300X0.5=150 m. For the calculation of pylon height, the ratio of Height of Pylon to total span is 0.075, 0.100, 0.125. here, ratio is kept 0.10. So, the height of pylon is 600X0.100=60 m. The height of pylon is taking above the deck. And below deck it Will be H/2=60/2=30 m. therefore, the total height of pylon is 60+30= 90m. The cables are anchored to the deck every 9m. which is allowed up-to 0.05 X length of main Span. [6] Each cantilever section' s deck is supported by 14 cables that are positioned on either side of the pylon in a semi-fan-like configuration. The cross beams on the longitudinal concrete girder are spaced nine meters apart from one another. The width of the carriage way is 7.5 m which covered by Reinforced concrete slab.

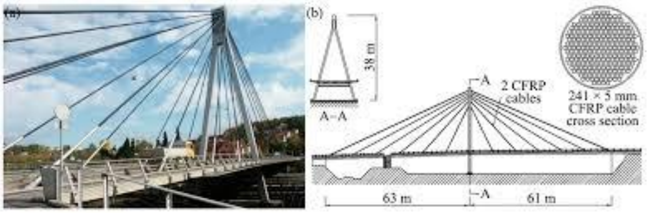

Fig -2: Stork Bridge, Winterthur, Switzerland

4.2 Steps involved for finalization Stay Cable Length

1.Calculating the ratio of back span to main span.
(Optimal range 0.25 to 0.55)
2.Establishing the cable spacing.
(Optimal range: 5-15 meters)
3.The rigidity of the deck is determined.
(Number of Longitudinal girders, girder depth, stay profile)
4.Calculating the cable's angle with the deck.
(Optimal angle 45 permissible range 25-65)
5.Finalize the pylon height while taking the height restriction into account.
(Optimum ratio of pylon height to main span 0.20-0.25 or 0.075,0.100,0.125 to total span)

Fig -3: Longitudinal View of Bridge

4.3 Design Calculations for the Cable Stayed Bridge

4.3.1 Parameters and Formulae: Consider 14 Number of Cables

1.Side span to Main span ratio
= LM/LS=150/300 = 0.5

2.Height of tower to Total span
= ht/LT = 90/600 = 0.15

3.Length of central panel in main span
= lc = 0.2LM
λ = EcAcL2
T /EGIG = 62000and83000
Where,
LS= Side span
LM= Main span
LT = Total Span
lc = length of one panel in main span
ht = height of tower
Ec = Modules of Elasticity of cable
EG = Modules of Elasticity of girders
Ac = Total area of cable
IG = girder moment of Inertia

4.3.2 Calculations: A) Cable angle with deck (For Cable No. 1)

θ = tan−1(h/a)
= tan−1(60/141)
= 23.05°

Table -2: Angle between stay Cable and Deck

Cable No.	Angle with Deck	Cable No.	Angle with Deck
1	23.05°	8	37.56°
2	24.44°	9	41.00°
3	26.00°	10	45.00°
4	27.75°	11	49.63°
5	29.74°	12	55.00°
6	32.00°	13	61.18°
7	34.59°	14	68.19°

B) Section Properties

Reinforced cement concrete is having grade of M-40 used for the actual designing the bridge structure. The cross-sectional area (A) and Moment of Inertia (I) is to be calculated for all components of bridge. As shown in Table.3 is showing the depth and Breadth of section likewise Girder, Pylon, cross beams for Girder and Cross beams for pylon. Mostly, circular section adopted for cable section for maximum tensile load carrying capacity. Cross beams for girder and pylon are connected to longitudinal girder as well as along the height of pylon.

Table -3: Section Properties of Bridge Components

Section Name	Depth/Dia M	Breadth M	C/S Area M^2
Girder	1.5	1.0	1.5
Pylon	1.5	1.5	2.25
Cable	0.052	-	2.25
CBeam _Girder	1.5	0.75	1.125
CBeam _GPylon	0.75	0.75	0.56

C) Material Properties

Material properties are defined with respect to each section's properties. Material properties are defined with respect to each section's properties. The material properties of the carbon fiber reinforced polymer cable may vary with respect to manufacturer.

Table -4: Material Properties of Bridge Components

Section Name	Elastic Modulus (KN/M^2)	Tensile Strength (KN/M^2)	Density (KN/M^3)	Poisson Ratio
Girder	$2.78X10^7$	-	23.56	0.2
Pylon	$2.78X10^7$	-	23.56	0.2
Steel Cable	$1.96X10^8$	1.67	77.09	0.3
CBeam_Girder	$2.78X10^7$	-	23.56	0.2
CBeam_Pylon	$2.78X10^7$	-	23.56	0.2
CFRP Cable	$2.05X10^8$	2.70	16.00	0.3

4.4 Design of Cable Stayed Bridge in MIDAS Civil

a. Define Material properties and Section properties like girder, pylon, cable, cross beams etc. Cross beam girder and cross beam for pylon are individually defined due to different compressive strength of concrete material. Provide M-40 grade of concrete for all sections.
b. By creating the first node at the (O, O) which will be copied and multiplied as decided dimension to create the components of Bridge. The main girder will be subdivided into the number of nodes. which will be connected by creating elements between two nodes. which shows the final length of girder. Likewise, pylon also draw. The cable profile can be drawn by connecting nods at deck and the nods at pylon at the assumed height while determining the cable angle.
c. Cables are modelled as truss elements to assign the unit cable force while analysis.it is then mirrored to obtain 3D model of the cable stayed bridge.
e. Longitudinal girder, pylon, and cross beams are modelled as beam elements. The shrinkage and creep are considered while performing nonlinear analysis of concrete structures as per IRC 112:2011. The elastic link is provided in between longitudinal girder and pylon, and the rigid links are provided at the foundation of the pylon and eighter side where bridge is simply supported.

Table -5: Initial Cable Forces in each cable

Cable No.	Pretension Force (KN)	Cable No.	Pretension Force (KN)
1	-1830.70	15	1815.28
2	2532.12	16	1019.41
3	3652.37	17	54.84
4	-234.60	18	1830.96
5	-559.06	19	505.98
6	647.09	20	-281.21
7	1527.23	21	1084.41
8	1592.25	22	3042.32
9	1196..94	23	1755.71
10	1104.47	24	1250.98
11	1044.03	25	1231.18
12	1034.45	26	1518.32
13	1325.35	27	1748.29
14	1568.99	28	1655.43

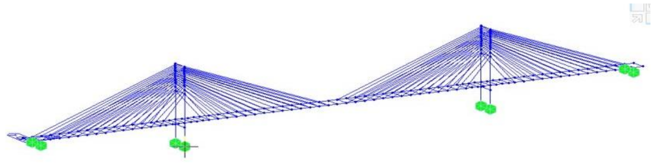

Fig -4: 3D Model of Cable Stayed Bridge

5 Results of ANALYSIS

5.1 Unknown Load Factor Optimization (ULF)

unknown load factor optimization function in MIDAS calculates the load factors to satisfy specific constraints like displacement defined for system Table 5 Shows pretension force in cable. Maximum force in cable observed in cable no. 22. If it is considered that cables initially stressed to 100 N/mm2. Then Number of cables can be calculated by following calculation.

1) Diameter(D) of Cable is 52 mm
2) Cross sectional area of cable will be
= π /4 X D2 = 2123.71 mm2
3) Force in cable = 2123.71X100/1000 = 212.37 KN
4) No. of cables
=pretension force in cable No.22/force in cable at initially stressed
5) No. of cables = 3042.32/212.37 = 14.32 14 Nos

6 Results and Discussion

1. CFRP cable-stayed bridges demonstrate excellent strength and stability, with the ability to support large spans with reduced material usage. The high tensile strength of CFRP contributes to the overall structural integrity and load-carrying capacity.
2. The lightweight nature of CFRP significantly reduces deadloads, leading to more efficient designs and potentially lower construction costs. This weight reduction also contributes to decreased demands on foundations and substructures.
3. CFRP cables exhibit superior durability, particularly in harsh environmental conditions where traditional materials might suffer from corrosion and degradation. This results in lower long-term maintenance costs and improved lifespan.
4. Although the initial cost of CFRP materials is higher than that of steel, the overall life cycle cost can be lower due to reduced maintenance needs and longer service life. Additionally, the lower weight can lead to savings in transportation and installation costs.
5. The use of CFRP materials can have a positive environmental impact due to the reduction in required material volumes and extended lifespan, leading to lower overall resource consumption and waste generation.

7 CONCLUSIONS

The design and analysis of CFRP cable-stayed bridges highlight the potential benefits of using CFRP materials in modern bridge construction. With superior strength, durability, and reduced weight, CFRP can significantly enhance the performance and longevity of cable-stayed bridges. While the initial costs are higher, the long term benefits, including reduced maintenance and extended lifespan, make CFRP an attractive option for sustainable bridge construction. Future research and development in this field can further optimize designs and expand the application of CFRP in the infrastructure sector.

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