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Comparative Analysis of Cable Stayed Bridges with CFRP and UHPC Concrete Deck Under Wind Load

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Abstract

Cable-stayed bridges are well-known for their efficient structural design, which utilises cables to support the bridge deck. It consists of one or more towers (or pylons) from which the bridge deck is supported by cables. The compressive force created by the tensile pressure in the cable wires has an impact on the bridge deck in addition to the direct traffic load. The weight of the deck is supported by a series of inclined cables, which are in tension that go directly to one or more vertical towers of a cable-stayed bridge. Towers transmit forces from cables to foundation by axial compression. Normally, cable-stayed bridges are constructed with RCC around 2000m span and beyond which steel bridges are preferred. In this study, the suitability of RCC strengthened with CFRP and UHPC materials as an alternative for RCC in cable-stayed bridges is investigated. The benefits of CFRP, such as high strength-to-weight ratio and flexibility, as well as those of UHPC, such as stronger compressive strength, durability, and low maintenance, make it a preferable choice to RCC. The performance of above bridges under dead and wind loads is evaluated using the finite element analysis software SAP2000. While applying the wind load, crucial parameters such wind speed and its direction are taken into account. The structural responses such as deflection, bending moment and shear force values gives a good comparison among these three bridge deck materials.

Keywords: Cable stayed bridge; UHPC; CFRP; Wind Load

Introduction

Bridge construction plays a significant role in human civilization growth. Long-term functioning of bridge constructions is crucial for transportation networks, making them an essential component of infrastructure [1, 4]. For spans up to around a thousand metres, cable-stayed bridges are more economical, but they also provide technical hurdles because of their distinctive forms and designs that appeal to architects. The three basic structural subsystems: girders (deck), towers (pylons), and cables make the cable-stayed bridges ambiguous [2]. Moreover, cable-stayed bridges are structurally efficient over large spans due to the interdependence of their subsystems [10, 15]. These bridge systems with spans of 700-1500m outperform suspension bridges in terms of mechanical strength, cost and aerodynamic performance [14].

As bridge deck is one of the major components of cable-stayed bridges, the selection of suitable deck material is very important. Bridge decks can be cast-in-place, precast, steel, wood, concrete, or other pavement systems that are supported by concrete or steel ,girders or beams (composites) [7, 8, 19]. They often determine the bridge's characteristics. Hence, the suitability of Carbon Fiber Reinforced Polymers (CFRP) strengthened RCC and Ultra High Performance Concrete (UHPC) bridge decks are investigated in this study. Composite cable-stayed bridges are becoming more and more prevalent in the bridge industry, and CFRP stay cables as well as decks are used nowadays [13]. CFRP materials are both strong and lightweight, making them ideal for improving load bearing capacity and extending the span of cable-stayed bridges to over 1000 metres [1]. Due to their extreme durability and corrosion resistance, CFRP cable- stayed bridges are ideal for use in abrasive settings such as straits and seas [3]. Special properties make CFRP materials ideal for large-span cable-stayed bridge construction [5]. The structural material Ultra High Performance Concrete (UHPC) is robust and long-lasting and makes it possible to design various parts efficiently [2]. High- performance structural materials like UHPC enable thin, light construction with little material. UHPC has exceptional durability, ductility, and toughness. It provides better corrosion and fatigue resistance, impermeability, and resistance to carbonization than steel does [4, 18]. Compared to regular concrete, UHPC has nine times flexural strength, twice the compressive strength, more resilience and has higher energy dissipation capability [20]. The creep coefficient of UHPC is approximately 15% lower than that of ordinary concrete. When it comes to flexural performance, UHPC constructions are half to one-third the self-weight of conventional concrete structures [17]. Because of its remarkable mechanical properties, research on bridge design using UHPC has attracted a lot of attention [18].

There are several studies that use CFRP and UHPC as alternatives to RCC bridge decks in the literature. The study by Xiong, W., et al. (2011), discussed special types of cable-stayed bridges with both CFRP deck and stay cables. Numerical simulations were used to compare the mechanical performance (static and dynamic) of composite cable-stayed bridges with various CFRP components. Along with structural performance cost analysis of different types of cable-stayed bridge was also compared and assessed [1]. Shao, Y., Shao, X., Li, L., & Wu, J. (2018), in their study suggested the best deck and bridge systems for super span cable-stayed bridges. The study uses finite-element software to examine the dynamic, and static performances of the UHPC deck cable-stayed bridge. It is discovered that the new bridge system has benefits over the traditional one, namely a main girder with a less axial force. The stress level of the UHPC in local models was examined using ANSYS [2].

According to Al-Rousan, R., Haddad, R. H., & Al Hijaj, M. A. (2014)., The deflection decreased and the cable stress increased as the stiffness of the deck increased [3]. Kim, S. T., Park, S. Y., Cho, K. H., Cho, J. R., & Kim, B. S. (2013)., showed that, using FRP deck instead of concrete reduces vertical deformation and cable stress below design code limits. Also, increasing deck width alters dominant response modes, and narrowing the deck decreases induced forces. Longer main spans reduce transverse shear forces [5]. In a study by Thu, A. N., & Khaing, S. Y. (2014) the structural properties of an A-shaped tower long-span cable-stayed bridge at three different wind speeds is analyzed and both linear static and moving load scenarios are included in its evaluation and design [6]. In Fawzy, A. M., El-Kashif, K. F., & Abdalla, H. A. (2022)., it has proven that the delta shape of pylon is most effective in terms of seismic performance, after the pyramid shape. Moreover, it has shown that the normalized shear force remains same when the deck width is changed for the same main span. When compared to other forms, pyramid shapes function better, displaying reduced forces in some directions. Narrowing the deck reduces generated pressures while widening the deck modifies dominant response modes. Transverse shear forces are decreased by longer main spans [8]. In an investigation by Ai, Z., Liu, H., Zhang, J., Zhang, C., Wang, C., Jiang, Z., & Xiao, R. (2023). concerning the mechanical and financial performance of cable-stayed bridges using ultra-high-performance concrete (UHPC) girders., it was observed that the axial force of the girder clearly shows the basic difference which is just one-third that of the steel system [14]. In their study, Giaccu, G. F., Briseghella, B., & Fenu, L. (2022, May), steel-concrete composite cable stayed bridges, the shear lag caused by the combination of axial stresses and bending is becoming more significant because composite technology allows for the creation of long spans that can support the weight of the structure and guarantee high deck stiffness [15]. Ma, C., Duan, Q., Li, Q., Liao, H., & Tao, Q. (2019)., showed that variable pressures on the girder are strongly influenced by the angle of attack of the wind, especially in the vicinity of wind fairings [16]. Wang, Y., Shao, X., Cao, J., Zhao, X., & Qiu, M, (2021). research revealed that due to the significant reduction in deck thickness, the deck's weight may be cut by 35%, which would reduce the deck's compressive stress under service loads [17]. Zhihua Chen's (2020) study demonstrated that augmenting eccentricity led to a decrease in bearing capacity and stiffness, while enhancing ductility [18].

After literature review, in the present study a cable stayed bridge of 2000m is selected. Structural behavior of cable-stayed bridges with CFRP strengthened RCC and UHPC decks is compared with RCC deck by measuring factors such as deflection, bending moment and shear force under dead load and wind load.

Materials and Method

Using the finite element analysis software SAP2000, a complete analysis of a cable- stayed bridge of span 2000m with different deck materials like CFRP strengthened with RCC and UHPC under dead and wind loads was done. In the present study, an RCC deck with M40 concrete and HYSD 550 bars were considered. The material properties of CFRP and UHPC are suitably selected from [1] & [2] respectively. For cables, Fe345 grade steel and for pylon M40 grade concrete is assigned. The material properties used in the present study is shown in Table 1.

PROPERTIES	
CONCRETE	Grade: M40
	Modulus of Elasticity= 31.62GPa.
	Weight per Unit Volume= 24.99 kN/m^3
	Poisson's Ratio= 0.2
STEEL	Grade:Fe345
	Modulus of Elasticity= 200GPa.
	Weight per Unit Volume= 76.97 kN/m^3
	Poisson's Ratio= 0.3
UHPC	Modulus of Elasticity= 45GPa.
	Weight per Unit Volume= 26 kN/m^3
	Poisson's Ratio= 0.2
	Compressive Strength= 170MPa
CFRP	Modulus of Elasticity= 228GPa.
	Weight per Unit Volume= 20 kN/m^3
	Poisson's Ratio= 0.32

Table 1: Material Properties of Bridge.

The cable-stayed bridge is modelled with a span of 2000m, in which centre to centre distance between the pylon is 1000m and end spans are 500m each. Both ends of the bridge are provided with fixed supports. For CFRP strengthened cable-stayed bridge, CFRP sheets with a depth of 0.1m are bonded onto the RCC deck with a link element. The geometric parameters of the bridge are presented in Table 2 and the bridge model is presented Fig.1.

Analysis

The models are analysed using SAP 2000 Software. To understand the static and dynamic behaviour of three different cable-stayed bridges, the responses of the bridge dead load and wind load are observed. The response parameters considered in the study are maximum deck deflection, bending moment and shear force in the bridge deck for all the three materials. The self-weight of the structure is considered in the software. Wind load is applied as per ASCE 7-10 in the software. The factors that needed to be assigned in the software for wind loading are taken from the code which is shown below in Table 3.

Where, For Exposure D, the kz value at different heights is provided in Table 27.3-1 of ASCE 7-10. The gust factor (G) is a multiplier that takes into account the impact of wind gusts on a building. The height of the structure, its natural frequency, and the terrain exposure category are among the factors that ASCE 7-10 states are used to determine the gust factor. To take into consideration the impacts of wind directionality on the structure, a coefficient known as the directionality factor (k_d) is included in the wind load calculations. The solid gross area ratio (SGAR) is a term used in structural engineering to represent the proportion of a structural member's or section's solid area to gross area.

MODEL DETAILS	
PYLON	Inverted Y Shape
	Total Height = 300m
	Height above deck=200m
	Height below deck=100m
	Top Pylon= 6m x 1.5m
	Bottom Pylon = 9m x 1.5m
DECK	Total Width=30m
	Depth = 0.5m
	Span =2000m
GIRDERS	2 No.s Fe345 I Section Steel Edge girders
	Height = 2.5m
	5 No.s of Fe345 I Section Steel Stringers
	Height = 1.5m
CABLE	Diameter = 0.5m
	Spacing = 10 m
	No. Of Cables = 400

Table 2: Geometric Parameter.

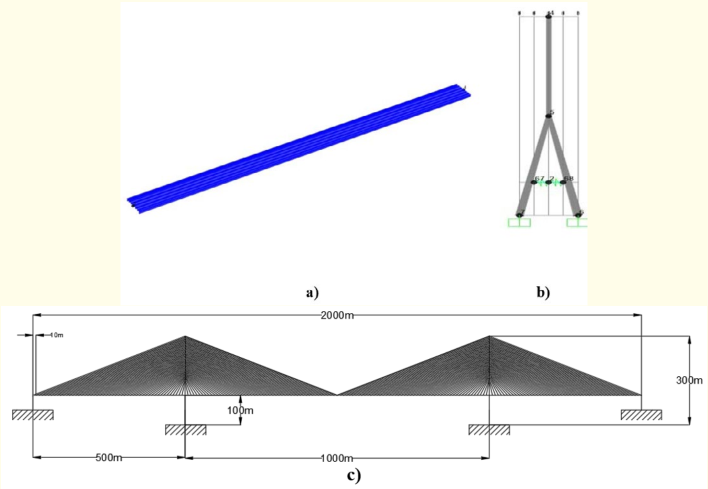

Figure 1: a) Bridge Deck b) Inverted Y Pylon c) 2 D Bridge Model.

Wind Load Factors	
Exposure type	D
kz	1.46
Directionality factor (Kd)	0.9
gust factor (G)	1.02
Solid gross area ratio (SGAR)	0.34

Table 3: Wind Load Factors as per ASCE 7-10.

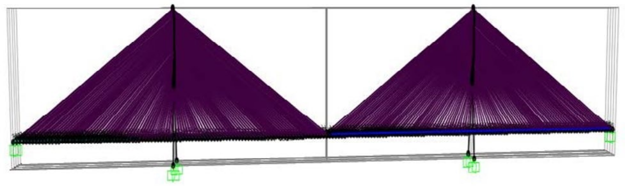

Figure 2: 3D Bridge Model.

Discussion

In the study, performance evaluation of RCC, CFRP strengthened and UHPC bridge deck under dead and wind load is done for a 2000m cable-stayed bridge.

Deflection parameter is recorded at a 200m interval along the span of the deck and presented in Fig 2. Due to dead load, the maximum deflection obtained for three different materials like RCC, CFRP strengthened RCC and UHPC are 0.528m, 0.459m and 0.534m respectively. The deflection of CFRP strengthened is 13.07% less than that of RCC. The deflection of UHPC is 1.14% more than that of RCC. From Fig. 2, it is very evident that the CFRP strengthened deck has less deflection compared to other two materials. The deflection limit due to dead load is L/450 as per AASHTO code, where L is the span of the bridge. Therefore, for a cable-stayed bridge with a span of 2000 metres, the deflection limits would be 4000mm (4 m). As the deflections obtained are in the limit, the models can be considered safe.

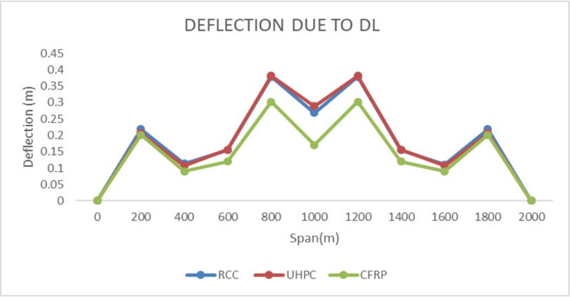

Figure 3: Deck Deflection due to Dead Load.

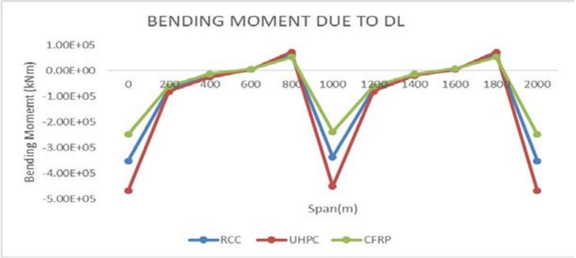

Figure 4: Bending Moment due to Dead Load.

Fig. 3 illustrates the variation of bending moment value along the span of the bridge at 200m intervals. 4.21×10^5 kNm, 3.19×10^5 kNm, 5.33×10^5 kNm are the maximum bending moment under dead load for RCC, CFRP strengthened RCC and UHPC respectively. The maximum bending moment of CFRP strengthened deck is 24.23% less than that of RCC and UHPC is 26.61% more than that of RCC. CFRP strengthened deck has a substantially lower maximum bending moment than RCC, indicating that it may disperse the dead load more efficiently, resulting in lower peak stresses. UHPC, on the other hand, has a larger maximum bending moment than RCC, because of the higher density compared to RCC for the same cross section.

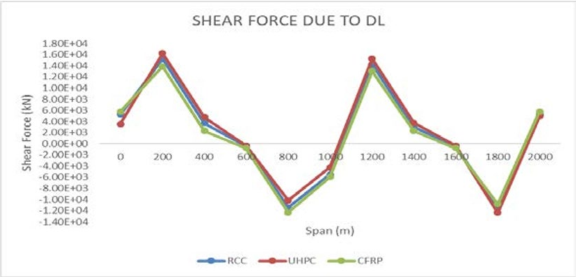

Figure 5: Shear force due to Dead Load.

For all three materials, the shear force profile is comparable, with peaks and troughs situated at the same span locations as shown in Fig. 4 for at regular intervals of 200m. This suggests that there is consistency in the load distribution among the various materials. From the shear force values it is seen that there is only marginal variation between values and in which UHPC exhibits the largest peaks, followed by RCC and CFRP strengthened RCC. This illustrates the differences in stiffness and material characteristics. When it comes to minimizing internal pressures brought on by dead load, CFRP strengthened deck is the most effective material because of its lowest shear force values.

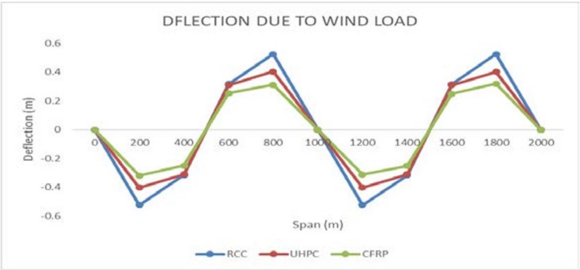

Figure 6: Deck Deflection due to Wind Load.

As per ASCE-7-10, wind load is applied and variation in deflection due to wind load in three different cable-stayed bridges was identified as shown in Fig. 5. The maximum deflection obtained for three different materials like RCC, CFRP strengthened RCC and UHPC are 0.562m, 0.326m and 0.415m respectively. When compared to RCC there is a percentage reduction in deflection of around 42% in CFRP strengthened deck and 26.16% in UHPC. With peaks at around 500 and 1500 metres and troughs at 1000 and 2000 metres, all materials exhibit a similar pattern of deflection. This suggests that the wind load along the span is causing symmetrical deflection behaviour. For cable-stayed bridges, deflection limits are critical due to the long spans and the potential for significant wind-induced vibrations.

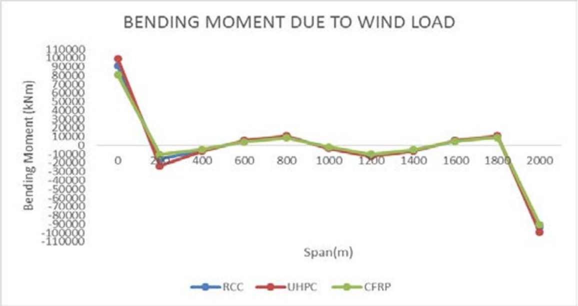

Figure 7: Bending Moment due to Wind Load.

The Fig.6 displays variable bending moments along the span at a regular interval of 200m and a notable bending moment at the supports, which are located at 0 and 2000 metres. 90772.14kNm, 80891.61kNm, 99278.24kNm are the maximum bending moments of RCC, CFRP strengthened deck and UHPC respectively under wind loading. Bending moment for CFRP strengthened RCC is 10.88% lower than that for RCC and UHPC is 9.37% higher than that for RCC. The considerable moment resistance needed at the supports is shown by the bending moment's abrupt drop from the supports towards the mid-span. The fixed or extremely restricted circumstances at these places, which oppose the forces generated by the wind, are the cause of the largest bending moments at the supports. When it comes to reducing bending moments, CFRP strengthened RCC performs the best, followed by UHPC and RCC. This shows that if wind-induced bending moments in cable-stayed bridges are to be minimised, CFRP strengthened deck may be a great option.

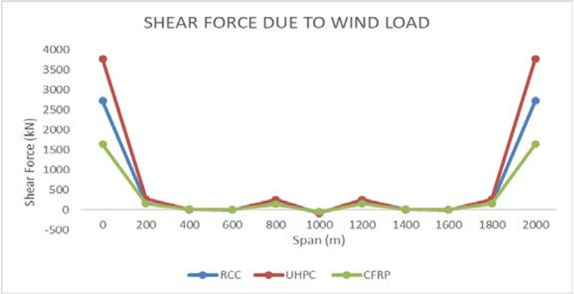

Figure 8: Shear Force due to Wind Load.

The Fig. 7 displays varied shear forces along the span and notable shear forces at the supports, which are located at 0 and 2000 metres at regular intervals of 200m. The considerable shear resistance needed at the supports is indicated by the shear forces' abrupt drop from the supports towards the mid-span. The supports exhibit the largest shear forces, with force values of up to ±4000 kN. The maximum shear force of RCC, CFRP strengthened RCC and UHPC are 2713.87kN, 1633.92kN, 3764.28kN under wind loading. CFRP bonded deck greatly enhances shear resistance under wind load, as evidenced by a 39.80% reduction in shear force against RCC. This makes CFRP strengthened RCC an excellent choice for reducing shear-related loads and potential failures in bridge constructions. The shear force for UHPC is approximately 38.71% higher than that for RCC. Along the span, the shear pressures decrease, and regular intervals of intermediate peaks and troughs are seen. UHPC and CFRP strengthened deck exhibit slightly lower shear forces than RCC, indicating their better performance in resisting shear forces.

Conclusion

All around the world, cable-stayed bridges are built in large quantities. For medium and large spans, this style of bridge is very competitive and cost-effective [7, 11]. When compared to other kinds of bridges, cable-stayed bridges have a particularly attractive appearance [3, 9]. Additionally, this kind of bridge closes the efficient span range gap between very long span bridges and ordinary girder bridges [12, 16]. SAP 2000 software is used in this study to examine the main span cable-stayed bridge, which is 2000m long. From the analysis, comparing Bridge decks with three different materials like RCC, CFRP strengthened RCC and UHPC under dead load and wind load showed that CFRP strengthened RCC is a better material compared to the other two.

The deflection of CFRP bonded RCC is 13.07% less than that of RCC. The deflection of UHPC is 1.14% more than that of RCC under dead load. The maximum bending moment of CFRP strengthened RCC is 24.23% less than that of RCC and of UHPC is 26.61% more than that of RCC under dead load. From the shear force values it is seen that there is only marginal variation between values and in which UHPC exhibits the largest peaks, followed by RCC and CFRP strengthened RCC. Given its superior performance in terms of deflection, bending moment, and shear force, CFRP strengthened RCC is an excellent choice for reducing deformations and internal stresses in the bridge deck under dead load. This can enhance the longevity and safety of the structure.

When compared to RCC there is a percentage reduction in deflection under wind load, of around 42% in CFRP strengthened RCC and 26.16% in UHPC. Bending moment for CFRP strengthened RCC is 10.88% lower than that for RCC and UHPC is 9.37% higher than that for RCC. CFRP bonded deck greatly enhances shear resistance under wind load, as evidenced by a 39.80% reduction in shear force against RCC. The shear force for UHPC is approximately 38.71% higher than that for RCC. When it comes to wind load performance, CFRP strengthened RCC outperforms RCC because of its large reduction in deflection, bending moments, and shear pressures, which increases structural longevity and efficiency.

It is clear from comparing the three materials that CFRP strengthened RCC performs best overall, followed by UHPC, while RCC performs least well under the specified loading circumstances. When striving for low deflections and internal stresses, CFRP strengthened RCC is the best material to use for cable-stayed bridge decks since it offers excellent structural performance and lifespan. While not as efficient as CFRP bonded RCC, UHPC is a good substitute for RCC, providing notable performance gains.

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